

Summary of the Original Contributions of the PhD Thesis

TRANSIENT MANAGEMENT IN
RECONFIGURABLE DIGITAL SIGNAL
PROCESSING SYSTEMS

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Introduction

The rapid development of technology makes it possible to consider solving such signal processing and control problems that was out of our reach due to their complexity, non-linear and/or time-variant properties, modeling difficulties, or distributed nature. In other words, required services in current applications demand modern engineering solutions to take into account increasing amount of information available only in run-time. For example, they must be prepared to react to failures, drastic changes inside the engineering solution or in the environment, and changing user requirements. These requirements can be satisfied with the run-time reconfiguration of the processing units directly connected to the environment.

During reconfiguration, due to the changes in configuration of the system, transient phenomena may appear, which can reduce the quality of services provided by the system. These transient phenomena are called reconfiguration transients in the terminology of the Thesis. Fundamentally, the reconfiguration transients increase the error of the system temporarily, for a sort time the system operates less optimally. However, in an unfavorable situation, the reconfiguration transients may cause the failure of the system, e.g., by inducing internal numerical overflow, or by overdriving actuators and through them some components of the environment. In mechanical systems, for example, these reconfiguration transients may cause fatigue of materials, and eventually fracture of components. As a result of an inappropriately conducted reconfiguration, the reconfiguration transient may cause the loss of system stability, for example in case of the control of non-linear physical systems, even if the systems realized in the individual configurations are stable. Therefore, the application of reconfigurable digital signal processing systems requires the detailed description of the transient phenomena observed during reconfiguration, and the development such methods, which allow the reduction of these reconfiguration transients to a level tolerable by the application.

According to the above mentioned facts, the examination and reduction of reconfiguration transients in reconfigurable digital signal processing systems, in short the transient management of such systems, have been selected as the topic of my PhD Thesis.

I examine the transient management of reconfigurable digital signal processing systems with the following restriction in my Thesis:

- Several level of implementation of the reconfiguration can be defined. In the Thesis, the signal-flow graph level reconfiguration of reconfigurable digital signal processing systems is considered. However, I take into account the properties of the hardware and software levels. The software and hardware levels influence the signal-flow graph level operation of the system through the design- and run-time resource requirements; therefore, I take into account and analyze the computational complexity of the proposed algorithms.
- I utilize the knowledge available in the field of hybrid systems, Switching Systems/Control, Gain Scheduling, and model-based control relevant to transient management, and my results may be utilized also in these fields.
- The system architecture depicted on Figure 1. is considered, and only the Reconfiguration Manager and Processing Units blocks are investigated. Naturally, the incidental influence of the environment is taken into account. The Systems Identification and Global Supervisor blocks are handled as blocks triggering reconfigurations; and therefore, I do not deal with their internal operation. All the other blocks are considered as predefined.
- The processing Units, which realize the reconfigurable digital signal processing system, are discrete-time, time-driven systems, and operate on continuous values. According to it, they can be investigated using the tools of classic digital signal processing.
- The Reconfiguration Manager block reacts to events, and due to these events it does transitions in a finite state space. In practice, this component is described and realized using hierarchical state-charts.
- I give the exact definition of reconfiguration transients, and the applied transient measures and criterions in the Thesis.
- The reconfiguration method defines the actual steps, in algorithms and time, taken while the old system is reconfigured to the new one. The reconfiguration methods have different implementation and transient properties, and even their implementation is application dependent. The following reconfiguration method types are investigated in the Thesis:
 - Reconfiguration by the switching of outputs (Output Switching),

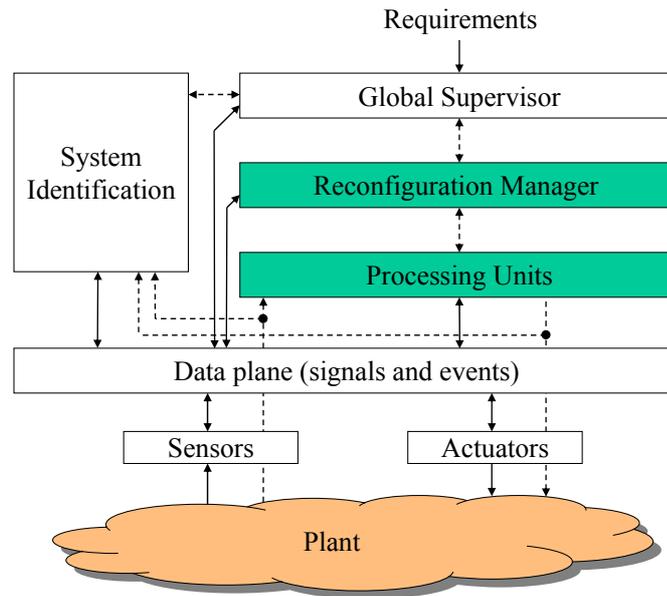


Figure 1: The architecture and the application environment of reconfigurable digital signal processing systems.

- Reconfiguration by the blending of the outputs (Output Blending),
 - One-step reconfiguration with the preservation of states (One-step Reconfiguration),
 - Multiple-step reconfiguration with the preservation of states (Multiple-step Reconfiguration),
 - Reconfiguration with the computation of suitable initial internal states.
- The process of transient management is labeled as passive if it utilizes no information available run-time, and it is label active if it uses such information. In the Thesis, passive transient management methods are examined primarily, because their run-time computational complexity is favorable most cases. In addition, some active transient management methods derived from passive methods are also introduced.
 - The investigation is restricted to cases, that employs linear, time-invariant, discrete-time (LTI-D) systems in the configuration between reconfigurations, in an open-loop setup, in filtering type applications, with single input and output (SISO).

Research Methods

The presented theoretical approach to reconfiguration transients of reconfigurable digital signal processing systems is based on the results available in classical signal- and systems theory, digital signal processing, and within these fields, specially based on the advances in the design and implementation of infinite impulse response (IIR) filters. A central role is played by the various descriptions of discrete-time systems and their hierarchy in the Thesis. The input/output descriptions; such as the unit-pulse response, unit-step response, transfer function, frequency response, etc.; are used to specify the configuration of the reconfigurable system. The theoretical investigations are based primarily on the state variable descriptions systematically derived from the signal-flow graph, or signal-flow network of the system. Special signal-flow graphs developed to realize digital filters, called realization structures; and through them, the theory of realization of such systems using fixed-point arithmetics are also utilized.

I validate and demonstrate my theoretical results using simulations. The simulations are realized using MATLAB programs written myself, applying various functionalities of the Control System and Signal Processing Toolboxes. The Matlab functions written myself can be grouped as the following:

- Functions to realize digital filters utilizing various structures, such as several normalized Lattice, resonator-based, and parallel structures.
- Coefficient computation functions for the structures, which make possible to compute the coefficients of the structure in the knowledge of the transfer function to be realized.
- Functions to compute the $\langle \mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D} \rangle$ matrixes of the state variable description corresponding to a given coefficient set and filter structure.
- Functions to realize the reconfiguration methods, run individual simulations, including infrastructure to measure run-time of simulations.
- Framework for setting up and running complex simulations, including functions used presenting the results.

Aside from Matlab based simulation, transient management methods are also presented using the TransMan Simulink block library developed for the Fault Adaptive Control Technology (FACT) project.

Section 3 of the Thesis gives the definition of the reconfiguration transient first. Then, it introduces transient measures and criteria to compare and characterize reconfiguration transients of the investigated transient management methods. The Thesis applies the energy of transient, actually the average of maximum of that, as the transient measure primarily. The configurations of the digital signal processing system are specified using signal-flow networks or graphs, and their coefficients, state variables, and the initial state variables. A given configuration is closely associated with its coefficient computation algorithms, which may be required for run-time coefficient computations and for certain reconfiguration methods.

Section 4 investigates passive transient management methods, and introduces new scientific results formulated in this field. New method is introduced to compute h , number of blending steps, based on the transfer function and the properties of the input signal, and the possibilities of the utilization of h in the Reconfiguration Manager block.

The average transient energy for white-noise excitation and the transient energy for sinusoidal inputs are expressed in closed mathematical form for one-step reconfiguration both with the zeroing or preserving the internal state variables during reconfiguration. The expressions are derived from an experimental setup constructed to transient investigation; later computationally viable methods of their determination and their application are given. The two reconfiguration methods are compared both theoretically and using simulations from the point of view of their transient properties in case of reconfiguration. A graphic geometrical interpretation is employed to show the role of the internal states, and in addition, the necessity of scaling and orthogonality for the one-step reconfiguration with state preservation.

It is shown in the Thesis, that the reconfiguration transients depends on the realization structure in case of the one-step reconfiguration with state preservation both theoretically and with simulations; and therefore, the selection of the realization structure can be considered as a passive transient management method. From the description of structure dependence a new variant of the resonator-based structure is derived, which has better transient properties for white-noise inputs. A new coefficient computation method is also introduced, that makes possible transient free reconfiguration for some special multi-sine inputs. The transient properties and structure dependence of the one-step reconfiguration are also demonstrated for simple closed-loop control system consisting a PID controller and a plant for both for state zeroing and state preservation.

Section 4 is closed with the investigation of the multiple-step reconfiguration with

state preservation, primarily by attracting attention again to the significance of the realization structure for this reconfiguration method also. It is shown there, that by linearly interpolating coefficient the reconfiguration transient can be dramatically reduced by selecting preferable realization structures, and a new tolerance-scheme interpolation method is introduced, and its favorable transient properties are also demonstrated using simulations.

Section 5 presents some active transient management methods. A novel active transient management method is derived, which takes into account the actual outputs available only run-time to compute h , which is the number of blending steps in case of the output blending reconfiguration method, with relatively low resource requirements. In addition, a method to design anti transient signals is also introduced.

Section 6 summarizes the original contributions of the Thesis. The open questions and viable future research directions are listed in Section 7.

Summary of Original Contributions

Thesis 1 *The structure dependence of output reconfiguration transients for the one-step reconfiguration with state preservation in case of digital filters, and its application as a passive transient management method.*

- 1. I have given a closed form expression of the average energy of output reconfiguration transient for white-noise inputs and the expression of output reconfiguration transient energy for sinusoid inputs; furthermore, for both cases I have elaborated the efficient computations of the expressions. I have demonstrated with examples that the proposed computational algorithms have more favorable computational complexity than simulations.*
- 2. I have shown that the the output reconfiguration transient depends on the realization structure in case of the one-step reconfiguration with state preservation; and therefore, the choice of realization structure can be applied as a passive transient management method. The statement has been verified employing simple example, the analytical examination of the expression of the average energy of the output reconfiguration transient, and with complex examples.*
- 3. I have given a graphic geometrical approach to describe the influence of realization structure to the reconfiguration transient. I have show that the uniform scaling of realizations affect the transient properties favorably, and the $\mathbf{K} = \mathbf{E}$ type orthogonality of the realization provides the most favorable transient properties for white-noise inputs in a worst-case manner. Based on these results I have proposed a modified, uniformly scaled resonator based filter structure with better transient properties.*
- 4. I have shown that in case of odd order filter, realizing a low pass or high pass transfer function, with cut-off frequency in the $f_c \ll f_s/2$ interval it is always possible to construct resonator based filter that has no transients in steady state for DC input. I have also shown that transient free controller reconfiguration can be guaranteed for control loops consisting a digital PID controller and plant described by a rational transfer function by selecting proper controller realization*

structure for constant setpoint signal, and in steady state.

The original contributions are published in [sp3,sp4,sp6,sp11,sp15,sp29,sp30].

Thesis 2 *Computation of transient properties of the one-step reconfiguration methods, and the comparison of them.*

- 1. I have given a closed form expression of the average energy of output reconfiguration transient for white-noise inputs and the expression of output reconfiguration transient energy for sinusoid inputs for the one-step reconfiguration method with state-zeroing; in addition, for both cases i have elaborated the efficient computations of the expressions.*
- 2. I have given the relation of the transient properties for the one-step state-zeroing and state preservation methods bases on the evaluation of the developed closed form expressions and the introduced graphical geometrical approach; furthermore, I have demonstrated this relation using examples.*

The original contributions are published in [sp11,sp16,sp29,sp30,sp33].

Thesis 3 *Extension to the design procedures and implementation of the multiple-step reconfiguration methods, and the deduction of new methods.*

- 1. I have given a design time method to compute the blending step number h for the output blending reconfiguration method. I have also given the practical applications of a global h for all configuration, and for $h_{i,j}$ for any i and j configuration pairs.*
- 2. A have developed an active transient management method to compute h based on real input signals in run-time to improve the transient properties of the multiple-step output blending method.*
- 3. I have shown how the structure dependence influences the transient properties of multiple-step reconfiguration with state preservation in case of coefficient interpolation, and I have formulated the structural requirements of favorable transient properties. Based on the these formulated requirements I have proposed a new tolerance-scheme based interpolation method for the multiple-step output blending method with state preservation; by using the new method, and by selecting proper realization structure, better transient properties can be achieved based on simulations.*

The original contributions are published in [sp5,sp18,sp22,sp23,sp29,sp30].

Application of the Results

There are several application areas in which reconfigurable digital signal processing systems may be used. However, modern vehicles raise such complex problems that can be solved using run-time reconfiguration perspective. There have been reconfigurable solutions applied in vehicles earlier. For example, using the terminology of the Thesis, the manual transmission systems (human supervision) or the classic hydraulic automatic transmission systems (robust, sub-optimal solution) reconfigures the transmission system of the vehicle according to the environment and requirements. In case of aircrafts, the application of slats, flaps, spoilers, and air-brakes, in certain designs variable wings, the state of retractable landing gears, or an unfortunate damage to the aircraft can be considered as a reconfiguration eventuating drastic changes in the properties of the aircraft. The vehicle must react to these changes, practically by reconfiguring its digital sensor and control systems according to the new circumstances, which raises the necessity of handling reconfiguration transients.

Unmanned/Uninhabited Air/Autonomous Vehicles (UAV) are also possible application area of reconfigurable digital signal processing systems because the changing environment in which the UAV must be able to operate, and the inevitable system failures bring up problems cannot be solved adequately using other possible approaches. The primary reason for this is that autonomous vehicles must be able to react algorithmically to such environmental and requirement changes that were commended to the imaginative human operator in all circumstances. Such systems must have control over reconfiguration transients, and they must be prepared specially to deal with them.

Furthermore, demanding robot control, industrial measurement and control systems, and communication technologies may be other application areas of reconfigurable digital signal processing systems.

A significant portion of the results introduced in the Theses has been developed for the DARPA Software Enabled Control (SEC) financed Fault Adaptive Control Technology (FACT) project. The main objective of SEC was to research the software intensive control of aircrafts (primarily fixed-wing and rotorcrafts) with special emphasis on UAVs. The main industrial partner of the project was Boeing Corporation. The De-

partment of Measurement and Information Systems was a subcontractor of Vanderbilt University, Nashville, Tennessee for the FACT project, and our main task was to support the digital signal processing related aspect of the project, especially considering the management of reconfiguration transients.

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- 1995-1998, OTKA T 017448, titled as Digital Signal Processing in Reconfigurable Systems.

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