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Unfolding-synthesis technique for digital pulse processing. Part 1: Unfolding

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ABSTRACT

The unfolding-synthesis technique is used in the development of digital pulse processing systems used in radiation measurements. This technique is applied to digital signals obtained by digitization of analog signals that represent the combined response of the radiation detectors and the associated signal conditioning electronics. The salient features of the unfolding-synthesis technique are first the unfolding of the digital signals into unit impulses, followed by the synthesis of digital signal processing systems with unit impulse responses equivalent to the desired pulse shapes. Part 1 of this paper covers the unfolding part of this technique.

1. Introduction

For more than two decades advancements in Digital Pulse Processing (DPP) have made it one of the most utilized techniques of pulse processing in radiation measurements today [1,2]. Early development of DPP was concentrated on direct synthesis of pulse shapes using sampled analog signals [3–5]. Other mathematically elaborated methods have also been considered and published [6,7]. In this paper we describe a technique that allows the synthesis of virtually any pulse shape, either exactly or as a close approximation. This method has been used extensively in creating algorithms suitable for real-time implementation. It has been also taught as part of university courses and lecturers [8]. However, no detailed and comprehensive description has been published prior to this paper. The unfolding-synthesis technique is applicable to linear signal processing systems that are either time-invariant or time-variant. In this paper, however, we will limit the discussions and the analysis to Linear Time-Invariant (LTI) systems. Unless explicitly noted otherwise, discrete-time systems will be considered.

2. Basics

Real-time digital pulse processing is accomplished using LTI systems (Fig. 1c) that are characterized and fully defined by their discrete-time impulse response $h(n)$ [9]. The impulse response $h(n)$ is the response of the system to the most fundamental digital signal – the unit impulse $\delta(n)$. The unit impulse is defined as:

$$\delta(n) = \begin{cases} 1 & \text{for } n = 0 \\ 0 & \text{elsewhere} \end{cases} \tag{1}$$

The weighted unit impulse $\delta_w(n)$ is the unit impulse multiplied by a constant, $w\delta(n)$. Thus, $\delta_w(0)=w$. The unit impulse and the weighted unit impulse are depicted in Fig. 1a and b respectively.

The multiplication of the unit impulse by a constant, as in the case of the weighted unit impulse, is one of the basic digital signal processing operations. Other basic operations include addition (subtraction), signal multiplication, and delaying or shifting of the digital signals. Fig. 2 shows the basic operations with their graphical representations and the corresponding mathematical expressions. Digital signal processing algorithms incorporate these operations in order to achieve more complex system responses.

The transformation of an input signal $x(n)$ into an output signal $y(n)$ by a LTI system is mathematically expressed as the output signal as a convolution of the input signal and the impulse response of the system. In the discrete-time domain the convolution is given by the following sum:

$$y(n) = \sum_{i=-\infty}^{n} x(i)h(n-i), \tag{2}$$

where $x(n)$ is the input signal being transformed into the output signal $y(n)$ by a causal LTI system with a unit impulse response $h(n)$. The convolution is commonly written using the star ($*$) symbol:

$$y(n) = x(n)*h(n) \tag{3}$$

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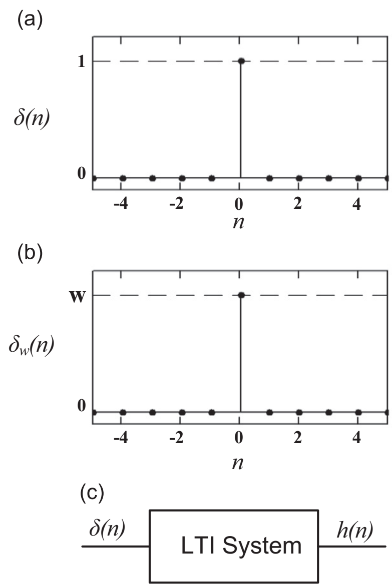

Fig. 1. (a) Unit impulse, (b) weighted unit impulse and (c) LTI system symbol and its unit impulse response definition.

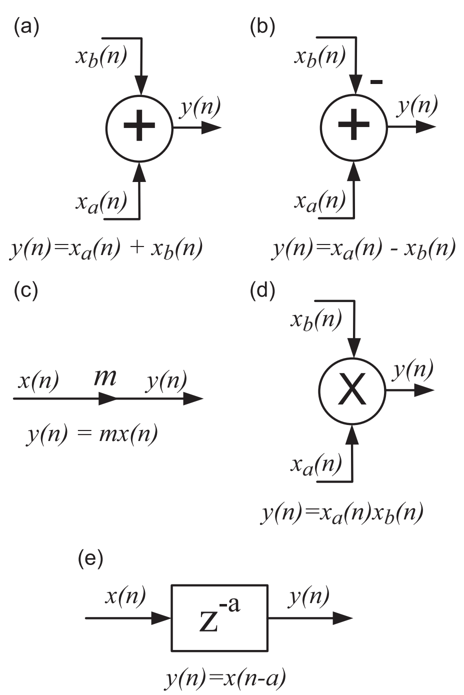

Fig. 2. Basic digital signal processing operations: (a) addition, (b) subtraction, (c) multiplication by a constant, (d) signal multiplication and (e) delaying or shifting.

The most important algebraic properties of the convolution are commutativity, associativity, and distributivity. We will use these convolution properties to explain and analyze various aspects of the unfolding-synthesis technique. These convolution properties are illustrated in Fig. 3.

3. Unfolding-synthesis technique

A system that implements the unfolding-synthesis technique is depicted in Fig. 4. Analog signals from radiation detectors and associated electronics are converted into discrete-time digital signals by a fast analog-to-digital converter (ADC). The ADC digitizes the analog signals by performing two operations: sampling and quantization. In the discussion that follows we consider that the quantization granularity is extremely fine and has little or no effect on the digital pulse processing algorithms. The quantization effects, however, should be taken into consideration when low-resolution ADCs are utilized by the DPP systems [10].

The digital signal that is produced by the ADC inherits the properties of the analog signal applied to its input. The analog signal is a convolution of the detector signal and the signal conditioning electronics. The detector signal can be approximated by a Dirac delta function $\delta(t)$ when it is very short compared to the DPP pulse shape. This approximation, for example, can be applied to signals from silicon drift detectors, small semiconductor detectors, and ultrafast scintillators. In such cases the analog signal applied to the fast ADC is characterized by the impulse response of the signal conditioning electronics.

In some cases, such as for large germanium detectors, the detector signal may vary in duration (charge collection time variation). In these cases, the pulse shaping in the discrete-time domain can be designed to unfold the impulse response of the signal conditioning electronics alone. The variability of the detector signal is then mitigated by features of the synthesized pulse shape, e.g., a flat top.

In other cases, the detector response may be combined with the response of the signal conditioning electronics. A typical example is a scintillation detector light pulse converted by a photo-multiplier tube (PMT) into an electric current. If the anode of the PMT is loaded by a C‖R network, the resulting voltage signal at the PMT anode will be defined as a convolution of the scintillation light signal and the exponential signal impulse response of the C‖R network. If the scintillator light emission pulse is a single time-constant exponential signal, then the anode signal will be a result of the convolution of the two exponential impulse responses. Digitizing this continuous-time signal will generate a digital signal that can be represented by the discrete-time convolution of two digital exponential signals.

For efficient implementation of the unfolding-synthesis technique, it is important to know the characteristics of the analog signals digitized by the ADC and to identify the impulse responses of the analog systems that will be unfolded. It is clear that these characteristics depend on both the response of the detector and the response of the signal conditioning electronics. The signal conditioning electronics are normally comprised of signal processing modules and networks with well-defined responses and transfer functions. These include detector preamplifiers, C-R and/or R-C networks, amplification stages, offset generators, base-line restorers, and other circuits that optimize the signal being digitized by the fast ADC.

The salient feature of the unfolding-synthesis technique is the transformation of the digitized analog impulse response into a unit impulse in the discrete-time domain. We call this process unfolding, or deconvolution. The unfolding transformation of a digital signal is performed by the unfolding system depicted in Fig. 4. The unfolding system has a unit impulse response $h_U(n)$ whose convolution with the digital signal from the ADC produces a unit impulse $h_N(n) * h_U(n) = \delta(n)$. Thus, the unfolding result is a convolution result and the unfolding is essentially a convolution. To avoid convolution–deconvolution tautology and confusion, the term "unfolding" is used in this paper rather than "convolution" [11].

The synthesis of the desired shape is accomplished by a synthesizing system with impulse response $h_S(n)$ identical to the system pulse-shaped signal, which we will reference to as an optimal pulse shape. The optimal pulse shape is determined by various factors such as noise suppression, counting rate requirements and other constraints. There is extensive material published on this topic [12–14]. This paper does not focus on selecting the