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Delta-Modulation Digital Processing of Videoinformation

D. N. Mishev, P. V. Petrov

The differential method of analog signal one-bit coding — the delta-modulation (DM) — is largely acknowledged as a means of economical digital coding in data transmission through a communication channel. The advantages and the shortcomings of the method in this respect are widely known [1, 2, 3]. Recently certain reliability consolidation of the delta-modulation as a method of informational coding has been noted [4] and first attempts at DM digital processing have been made [5, 6, 7, 8] but they were more of an incidental rather than systematic nature.

On the other hand, because of the lower rate of the DM binary digital stream compared to the normal or logarithmic PCM at adequately satisfiable quality of coding (referring to the signal-to-noise ratio SNR) and of the considerably simplified instrumental design compared to other coding methods (for instance DPCM), we may consider the DM method as particularly favourable for videoinformational digital processing.

The purpose of this paper is to present a systematic overview of the DM possibilities in digital processing in general and to consider some specific processing properties of this coding type. As far as the authors are informed, this may be a first approach of that kind.

1. Differential Calculations and Delta-Modulation

The differential algorithms with finite number and step size represent a significant portion of the contemporary digital methods applied with finite state machines (both in step and operational number).

While the differential calculus provides the principles, it can be shown that the DM is a natural basis for applying these principles in a general sense. For instance, we can find analogy between the differential algorithms of a uniform set and the synchronous DM or between the differential calculus of nonuniform interpolation sets and some specific types of asynchronous DM. The linear synchronous DM represents the input signal only by constant finite differences [1] although there are varieties (adaptive and/or asynchronous) [9, 10], where these differences are distinguished between themselves. The inear DM does not represent the input signal itself through the finite differences of the 1st order but rather its linear interpolation (with splines of the 1st order, therefore the macrointerpolation, as far as they interpolate among themselves in certain cases, is of "zero" order), and the accuracy is provided on account of the increased clock frequency (i. e. increased number of interpolation blocks).

Let us consider a function of a variable determined over a discrete set of equidistant points, i. e.

$$\{f_k \mid f_k = f(x_0 + kh),\ h = \text{const}\}_{k \in M}, \tag{1.1}$$

$$x = \{x_k \mid x_k = x_0 + kh,\ h = \text{const}\}_{k \in M}, \tag{1.2}$$

$$M = \{m \mid |m| \in N_0\},\ N_0 = \{0, 1, 2, \dots\}, \tag{1.3}$$

where M is the index set of the interpolation set. The differential operator can be determined [11] as

$$\Delta f(x_i) = f(x_i + h) - f(x_i) = f_{i+1} - f_i. \tag{1.4}$$

The differential operator contribution to the various arithmetic processes is of particular importance to the further examination of the relationship between the signal digital processing and the delta-modulation processing system. This operator is linear [1]. Its effect on products of two functions, for instance, can be represented by

$$\begin{gathered} y_i = \varphi_i \psi_i \\ \Delta y_i = \Delta[\varphi_i \psi_i] = \varphi_{i+1} \Delta\psi_i + \psi_i \Delta\varphi_i = \varphi_i \Delta\psi_i + \psi_i \Delta\varphi_i + \Delta\varphi_i \Delta\psi_i. \end{gathered} \tag{1.5}$$

The operator for the n-th derivative can be represented as (1.6) [12, 13] based on the differential Table for uniform interpolation set and sufficiently differentiable function

$$\frac{d^n}{dx^n} = \left[\frac{1}{h} \ln(1 + \Delta y)\right]^n = \frac{1}{h^n}\left(\Delta y - \frac{1}{2}\Delta^2 y + \frac{1}{3}\Delta^3 y - \dots\right)^n \quad x_i \in X. \tag{1.6}$$

Then for the first derivative it yields

$$y'_i \approx \frac{1}{h} \Delta y_i \tag{1.7}$$

as approximation for functions with finite spectrum at sufficiently populated interpolation set or

$$\# M > A, \tag{1.8}$$

where $\# M$ is the cardinal number of the index set and A depends on the spectrum type, i. e. condition (1.8) is equivalent to sufficiently large clock-frequency in the DM processing system

$$f_c > f_a, \tag{1.9}$$

where f_c is the clock-frequency of the DM system.

There are other types of numerical differentiation [12], appropriate to the given case.

At functions of two arguments $z = f(x, y)$, which represent the natural generalization of different picture types, we can define by analogy (1.4) a linear differential operator [12, 14]. Referring to the latter, the interesting processing cases, e. g. (1.5), (1.7), can be generalized as well.

The prediction process in delta-modulation models another approximative curve with spline functions of the respective order, following the main process in the discretization points

$$(1.10)\qquad \delta^k_\tau : \begin{cases} z_{i-1} = \operatorname{sign}(c_i - y_{i-1}), & z_i \in \{-1, 1\} \\ y_i = y_{i-1} + z_{i-1}, & k, k = \text{const}, \end{cases}$$

is valid for the linear DM, where δ^k_τ is the delta-transformation of the analog signal, $x(t)$ by the DM coder with k-step and duty cycle interval $\tau = \frac{1}{f_c}$; y_i is the approximated signal respective value $c_i = c(t_i)$ and z_i is the delta-modulator output jump, normalized to the step, prior to encoding into a binary code. The approximating process y_i can be represented as resulting from the two corresponding sequences of the differential table for y_i, and the specific feature of the Table is the fixed value of the first difference.

The differences available in the differential tables for the input signal and the approximation would result mainly from the distortions within the coding process, i. e. from the quantizing noise and from the slope overload noise. If we average within a given finite interval $T = n\tau$ by the dependence

$$(1.11)\qquad \Delta y_m = y_{m+1} - y_m = k \sum_{i=(m-1)n+1}^{mn} z_i,$$

i. e. if we build up the first two columns of the differential table over the depopulated interpolation set $x^m_c - x^m_y$, where the dependence

$$(1.12)\qquad \# x^m_c = \frac{\# x^i_c}{n}$$

is valid, then between the cardinal numbers of the index sets there is a certain approximation of the two tables in the case of optimal signal quantization $c(t)$ (with respect to the signal-to-noise ratio — SNR). Otherwise, the approximation differentiational table would appear in a rather tough form, compared to the input signal table.

By analogy, in other DM types there is an interrelation between the output sequence of the DM coder variations

$$(1.13)\qquad z\delta_c = \{z_i\}_{i \in N}$$

and the differential table of the input signal, respectively.

2. Delta-Modulation Operations

If we satisfy the familiar requirements [15] for an optimal DM coder, we may consider x^q_i for an accurate digital representation of x^q_i by amplitude.

The delta-transformation of the input signal $c(t)$ can be represented as a binary sequence

$$(2.1)\qquad \delta_c = \{B_i\}_{i \in N}, \quad B \in \{0, 1\},$$

where N is the index set.

If $f(t)$, $u(t)$ and $v(t)$ are the actual input signals, represented by time functions with a finite spectrum, and their DM transformations are $\delta(f)$, $\delta(u)$

and $\delta(v)$ and the operation $F_i^q = U_i^q * V_i^q$ is effected, the processing could be subdivided into three classes depending on the result type.

a) the output gives the finite differences, $\Delta F_i^q = F_{i+1}^q - F_i^q$ in digital form coded into the respective binary code.

In that case the process can be represented as an output of a differential coder with a pulse-code modulation (DPCM) which encodes the respective resulting signal, composed by the DM approximations of signals and $u(t)$ and $v(t)$

(2.2) $$\Delta F_i^q = \varphi(\delta u, \delta v, *);$$

b) the output is represented in DM type $B_i^f = \psi(B_i^u, B_i^v *)$, where B_i^f, B_i^u, B_i^v are respectively the i-th binary symbols from the corresponding sequences, i. e.

(2.3) $$\delta f = \psi(\delta u, \delta v, *);$$

c) the result is represented as a DM approximation F_i^q before or after LF-filtering, decoded respectively, i. e. both result processing and decoding are effected

(2.4) $$F_i^q = \chi(\delta u, \delta v, *).$$

Both cases (a) and (b) permit uniquely the direct digital representation of the signal in the respective system code (by accumulation of F_i^q from (2.2) and (2.3)). Case (c) is valid when the transformation χ is invariant with respect to the binary sequences δu, δv or to their resultant and the operation $*$ is mostly realized by variations of the DM decoder parameters.

3. Spatial Invariant Transformations of Pictures

The picture $I = B(x, y)$ can always be represented through a screen scanning system as a function of one argument $B(t) = B[x(t), y(t)]$ through the evolved functions $f_x(t)$, $f_y(t)$ [16, 17, 18], where

(3.1) $$U_I = U[B(t)] = U\{B[x(t), y(t)]\}$$

is the output signal of the screen system.

Let transformation $\delta_\tau^k(U_I)$ be effected by the DM decoder (1.10). It will transform the continuous signal of the evolving system $u(t)$ into the binary sequence δu

(3.2) $$\delta_\tau^k : u(t) \rightarrow \delta u(i).$$

Therefore, the picture I is transformed into the sequence δu, through the composition of the screen system and the DM coder (Fig. 1). When decoding the δu by appropriate decoder $(\delta_\tau^{k'})^{-1}$ the signal $U'(t)$ could be obtained which corresponds to the picture I'. Thus the spatial invariant operations concerning contrast variations, inversion, peculiarity outlining, and quantization [20] can be readily effected.

We call spatial invariant operations those which accept translation i. e. when the operational composition over the picture φ and the translation $T_{a,b}$ are commutative [19].

If the operation φ is such that $\varphi[f(x, y)]$ depends uniquely on $f(x, y)$, i. e. there exists an $\chi(f)$ such that

(3.3) $$\varphi\{f(x, y)\} = \chi\{f(x, y)\} = \chi(f_i), \quad \forall f \in \varphi, \ \forall (x, y) \in S$$

is valid, where φ is the picture set within which the operation φ is realized in the definition region of S, then φ would be the by-element operation for the picture I. If χ is linear and of the type

$$\chi=\chi(f_i)=p \cdot f_i. \tag{3.4}$$

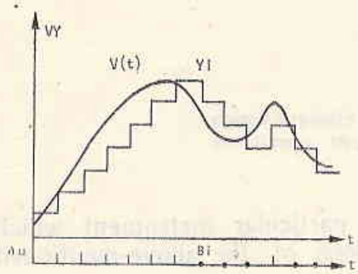

Fig. 1. Picture I is transformed into the sequence δu

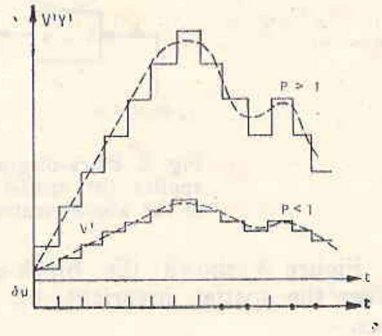

Fig. 2. Spatial invariant transformation of picture by the composition (3.5)

t could be easily effected by the composition between the direct and reverse DM transformations.

$$\delta_\tau^{k_2} \circ (\delta_\tau^{k_1})^{-1} \tag{3.5}$$

according to the scheme

$$I \xrightarrow{f_{xy}} U(f) \xrightarrow{\delta_\tau^{k_1}} \delta_u \xrightarrow{(\delta_\tau^{k_2})^{-1}} U'(f) \xrightarrow{f_{xy}^{-1}} I'. \tag{3.6}$$

The new signal $U'(t)$ amplitude will attain the value

$$A_1=A_0\frac{k_2}{k_1}=A_0 p. \tag{3.7}$$

Obviously picture I is transformed into I' (3.6), where $\varphi: I \rightarrow I'$ and $\varphi[f(x, y)] = \chi(f_i(x, y)) = kf_i$ as far as the picture I geometry is not deformed, φ is the spatial invariant and actually

$$\forall f \in \varphi,\ \forall (x, y) \in S,\ T_{a,b}[\varphi(f)] = T_{a,b}[kf_i] = kf_i(x-a, y-b) = k(T_{a,b}(f_i))$$

$$= \varphi[T_{a,b}(f)] \Rightarrow T_{a,b} \circ \varphi = \varphi \circ T_{a,b}. \tag{3.8}$$

Figure 2 shows the cases $p>1$, $p<1$. Under operation we understand precisely the composition (3.5), i. e. the realization of the linear by-element operations of the type χ by DM is adequate to the signal coding of the evolving system $U(t)$ by the point $\delta_\tau^{k_1}$ in the plane of the linear DM transformations and its reconstruction at point $\delta_\tau^{k_2}$ from the same plane [20].

$$\begin{array}{ccc} I & \xrightarrow{\varphi} & I' \\ \downarrow & & \uparrow \\ U(t) & \xrightarrow{\delta \circ \delta^{-1}} & U'(t) \end{array}$$

This type of processing is of the class (2.4) because the output DM sequence δu is invariant with respect to the operation. By analogy, there could be realized operations of contrasting over determined levels, outlining of specifics and others [20] by appropriate restrictions over φ of the by-element operations.

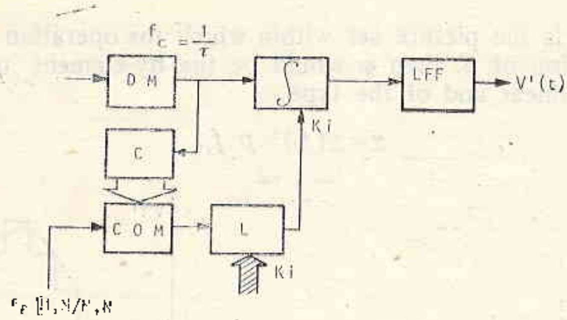

Fig. 3. Block-diagram of that particular element which applies the spatial invariant by element operations of the above-mentioned types

Figure 3 shows the block-scheme of that particular instrument which applies the spatial invariant by element operations of the above-mentioned types.

4. Scale Transformations*

A single representation of the signal $U(t)$ (3.2) is realized by the transformation δ_τ^k (3.2), which is invariant with respect to the scales of the two coordinates of the signal and to the coordinates of the picture itself, respectively, since it is adequately represented by the screen system. In contrast to (3.5), here the composition will be

$$\delta_{\tau_1}^{k} \circ (\delta_{\tau_2}^{k})^{-1} \tag{4.1}$$

because the scale transformations over picture I are attached to it by $U(t)$ of the screen system. It is clear that all similar (purely scalar) operations will be represented in the plane of the DM transformations [21] by segments parallel to the abscissal axis $O\tau$. The dependence between the coded and decoded signal in that case will be

$$U'(t) = U\left(t\frac{\tau_2}{\tau_1}\right), \tag{4.2}$$

i. e. in fact we have "extension" ("compression") of $U(t)$ up to $U'(t)$ or the linear picture scale variation takes place because of deformation in the temporal axis in the screen system by φ, obviously the signal temporal deformations $U(t)$ evolve frequency deformations, according to the compression theorem of the Fourier transformation and the signal $S(\omega)$ spectrum becomes

$$\begin{array}{ccc} I & \xrightarrow{\varphi} & I' \\ \downarrow & & \uparrow \\ U(t) & \xrightarrow{\delta,\delta^{-1}} & U'(t) \end{array}$$

$$S'(\omega) = \frac{\tau_2}{\tau_1} S\left(\frac{\tau_1}{\tau_2}\omega\right), \tag{4.3}$$

i. e. the signal spectrum components $\{\omega_i\}_{i\in N}$ will transform into $\left\{\omega_i \frac{\tau_1}{\tau_2}\right\}_{i\in N}$, and the period of the transformed signal $U'(t) = U'\left(t + \frac{\tau_2}{\tau_1} T'\right)$ will be $T' = kT$.

* By scale transformations over I we understand here the transformations of the linear scale towards the rapid scanning of the screen system, for instance for the sweep f_x.

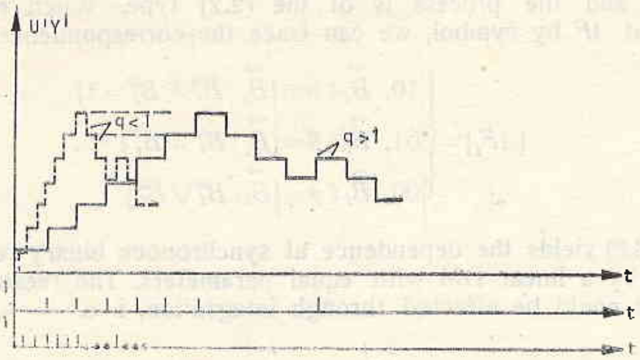

Fig. 4. Scale transformation

The new signal $U'(t)$ will be received at the DM decoder with the same SNR as in possible reconstruction of $U(t)$ in the same coding point of the $\delta_{\tau_1}^{t}$ signal, i. e. both direct and reverse DM transformations are equally optimal with respect to the SNR. Indeed, the familiar formula [1] for the SNR_{max} yields

(4.4) $$SNR_{max}=\frac{c\cdot f_c^{3/2}}{f_0\cdot f_m^{1/2}},$$

where $f_c=1/\tau$ is the DM clock frequency, f_m is the boundary frequency of the lowpass filter LPF permeability into the DM coder, and f_0 is the frequency of the processed harmonic signal, i. e. SNR is invariant with respect to the frequency region deformation equal for both the decoder and the signal.

Figure 4 shows the two possible cases of temporal scale changes of $U(t)$ at $q=\frac{\tau_2}{\tau_1}>1$ "extension" and $q<1$ "compression". Because of the screen system the picture would change geometrically along the same axis proportional to q or

(4.5) $$\delta_{\tau_1}\circ\delta_{\tau_2}^{-1}[f(x,y)]=f(qx,y)=\varphi(f).$$

Operations of type (4.5) are intercommutant at certain conditions [21], which significantly facilitates repetitive processing.

5. Application of Some Arithmetic Operations

5.1. Addition

The operation can be represented as

(5.1) $$F_i^q=U_i^q+V_i^q.$$

By analogy with the differential operator effect in the arithmetic operations point 1, [11] the addition in this case could be represented by $z\delta u$ and $z\delta v$

(5.2) $$\Delta F_i=z_i^u+z_i^v.$$

It can be proved that

(5.3) $$\Delta F_i\in\{-2,0,2\}$$

is valid [22] and the process is of the (2.2) type. When representing the DPCM output ΔF by symbol, we can trace the correspondence

$$|\Delta F_i| = \begin{cases} 10, & \vec{B}_i \in \alpha = \{\vec{B}_i \mid B_i^u \wedge B_i^v = 1\} \\ 01, & \vec{B}_i \in \beta = \{\vec{B}_i \mid B_i^u + B_i^v\} \\ 00, & \vec{B}_i \in \gamma = \{\vec{B}_i \mid B_i^u \vee B_i^v\} \end{cases} \quad . \tag{5.4}$$

Expression (3.8) yields the dependence at synchronous binary sequences δu and δv obtained by a linear DM with equal parameters. The reestablishing of the actual values could be effected through integration, i. e.

$$F_i = \sum_{j=0}^{i-1} \Delta F_j > \sum_{j=0}^{i-1} (z_j^u + z_j^v). \tag{5.5}$$

The logical scheme through which (5.2) is transformed into (5.4) is shown in Fig. 5 as the integration over (5.5) can be effected by reversive counter shown with dashed line (the amplitudinal recovery in the differential methods is reduced always to integration and therefore this counter is typical for any similar operation).

In general the addition of n-variables could be effected also by the corresponding DM transformations [22] and into the three possible types — (2.2), (2.3) and (2.4), respectively.

It can be shown that the subtraction reduces to logic inversion composition of one sequence and addition [22] (Fig. 6).

5.2. *Multiplication*

Let us assume necessary to perform operation

$$F_i = U_i V_i. \tag{5.6}$$

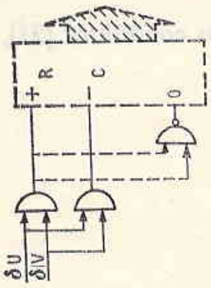

Fig. 5. Addition of 2-variables

If the differential operator affects this expression and the finite difference (1.5) is formed when replacing the corresponding differences with the DM jumps z_i^u and z_i^v, we can obtain

$$\Delta F_i = z_i^v \sum_{j=0}^{i-1} z_j^u + z_i^u \sum_{j=0}^{i-1} z_j^v + z_i^u z_i^v \tag{5.7}$$

at the input signal. Expression (5.7) yields the digital jump when a product of the respective DM transformations δu and δv is formed with equal parameters τ and k. In integrating the differences we can obtain the product itself.

The adding procedure does not express clearly the advantages of any of the three representations of the output signal (2.2), (2.3) and (2.4). The multiplication procedure will yield a very complicated solving rule (5.7) at output of the (2.3) type [22], and the algorithmic noise of the operation will be significant. This noise can be distributed as additional into both categories of DM noise—from quantization N_Q and from slope overload N_s. The output realization

(2.4) is impossible because of changes in the invariance condition (point 2.c). A block-scheme of the (2.2) type is shown in Fig. 7.

The reversive counters RC U and RC V integrate the corresponding binary sequences δu and δv. The multipliers with values $N \times 1$ in fact determine only the

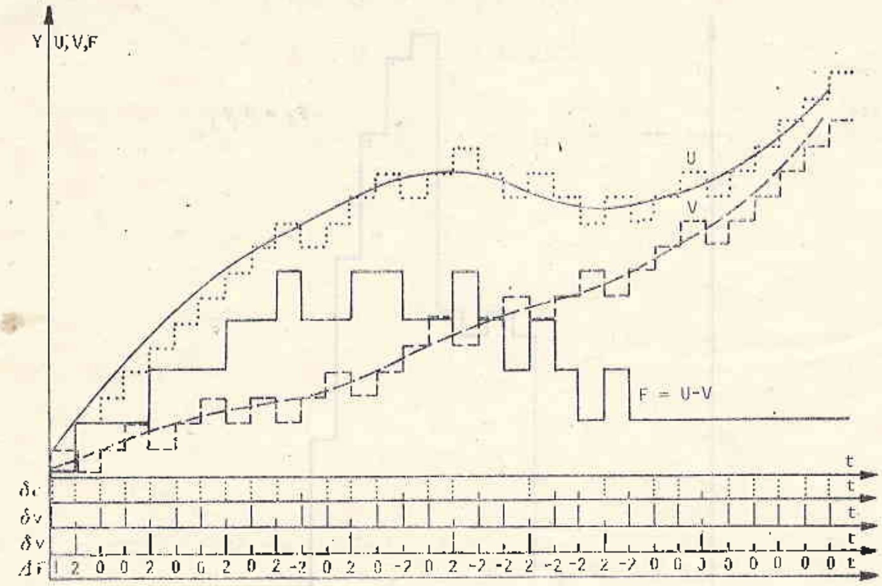

Fig. 6. Subtraction reduces to logic inversion composition of one sequence in addition

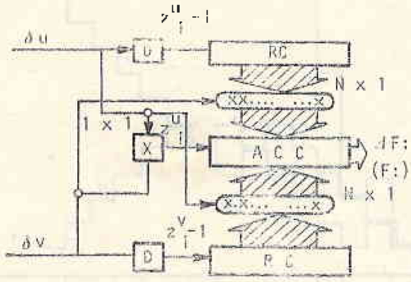

Fig. 7. Block-diagram of the multiplication, (2.2) type

sign of the result yielded by the counters when adding that to the accumulating adder. When the annulation of the accumulating adder is effected at each duty cycle, ΔF_i will be obtained at its output in the opposite case F_i could be accumulated in the same adder. The multiplier of value 1×1 determines the sign of the adder unit in the LSB order of the adder. Figure 8 shows the result approximations of the respective signals of the binary sequences and digital values of ΔF_i.

This technique could result in a great number of operations which are interesting for the videoprocessing of the spectrozonal scan videoinformation for the needs of the remote sensing. For instance, in a similar way we can present the Riemann and Štilte's integrals [23] and some integral transformations as well. The contouring of some specific features could be effected also by this technique, once by the respective DM analogies to (1.7) [24] in different directions [25, 28, 27] and also when realizing some gradient operators

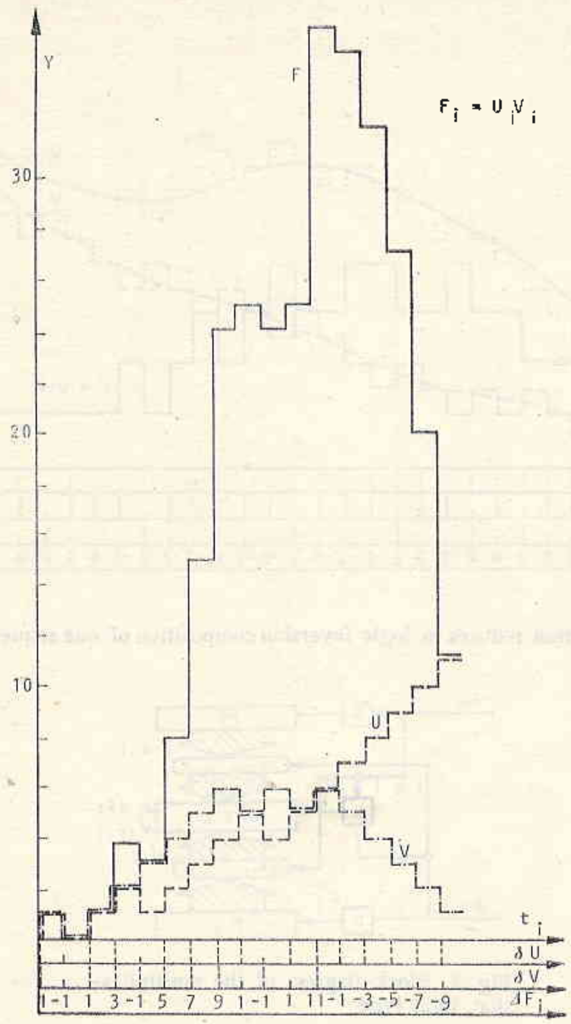

Fig. 8. The result approximations of the respective signals of the binary sequences

by DM, for instance [26, 29, 27]. Simultaneously we can measure some parameters of the subjects, such as surface [30].

Particularly interesting for these aims is the determination of uniform subjects (with respect to the spectrum) from the multispectral scan videoinformation. One of the principal requirements for such a procedure is the real time mode of the reproductive system. The DM processing system separates the uniform videoinformational files by recording the alternative series of the output binary sequence δu [27] for each spectral channel.

By the logical intersection between the unions of the different subject chords in each channel

$$(\bigcup_i u_i^{k_1}) \cap (\bigcup_j u_j^{k_2}) \cap \dots \cap (\bigcup_p u_p^{k_N}) = v \tag{5.8}$$

we obtain the homogeneous subject v, represented in the screen system by the respective restrictions of the videosignals in each channel $u_i^{k_i}$. By such separation of homogeneities it is possible to effect various types of regularization to a different extent.

6. Possibilities of Instrumental Programming in Different Modes

When designing a TV-instrument for videoinformational processing which employs a single DM processing system, it is of particular importance to minimize the instrumental part.

The introduction of instrumental programming is of specific advantage because it provides for the use of a universal module in effecting a large number and types of operations.

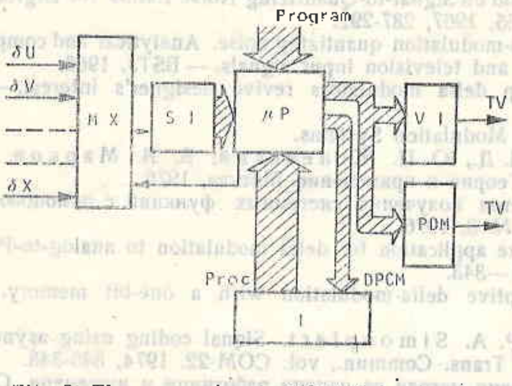

Fig. 9. The processing is effected by the microprocessor

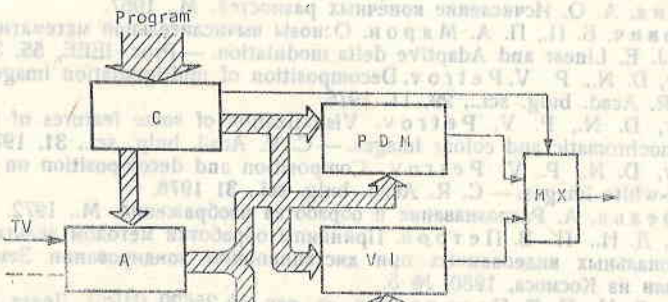

Fig. 10. The microprocessor is used as a controller

With the introduction of large integral schemes into practice, considerable possibilities to universalize the instrumental part appeared [33], e. g. the new generations of microprocessors are particularly applicable to the binary sequences, especially in analog signal processing [31]. Of course, videoprocessing sets its specific requirements on the design of such instruments and we can divide them into two groups:

a) instruments where most of the processing is effected by the microprocessor sequences (Fig. 9);

b) instruments where the microprocessor is used only as a controller (Fig. 10).

The instruments in Fig. 9 can be successfully applied in cases when the digital streams under processing do not exceed significantly their permeability, i. e. these could be fast and high-speed bipolar microprocessors.

Inversely, the version in Fig. 10 does not require fast operation of the processor, because it commutates the instrumental part when realizing the various operations. The realization itself should be fast.

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Цифровая обработка видеоинформации при помощи метода дельта-модуляции

Д. Н. Мишев, П. В. Петров

(Резюме)

В работе сделана попытка систематизировать обзор возможностей метода дельта-модуляции для осуществления некоторых операций при обработке видеоинформации. Показаны связь разностного исчисления и дельта-модуляции, а также возможности этого метода для реализации пространственно-инвариантных и масштабных трансформаций некоторых арифметических операций.

Сделана классификация обрабатывающих систем с дельта-модуляцией как по отношению к принципам работы, так и по отношению к организации аппаратной части.