AN EXTENDED SPECTRAL OBSERVER FRAMEWORK IN APPLICATION TO MULTIPLE-CHANNEL OPTICAL MEASUREMENTS

Evgeny Seider, Naum Chernoguz
OrSense Ltd, Rehovot, Israel

Seider@OrSense.com, ChernoguzNaum@hotmail.com

ABSTRACT

The problem of multiple-wavelength optical measurement arises in oximetry, glucometry and other biomedical fields. Due to the apparatus complexity, commercial devices, however, suffices in few, say 2-3 wavelengths. The study describes design principles of a multiple-channel optical system with increased number of wavelengths. The development is performed with the emphasis on the DSP and its adjustment to the application requirements. Several basic principles of signal processing are involved. Conceptually, the DSP framework represents an extended spectral observer, where each resonator relates to a probe waveform or, in contrary, to disturbance. Among other parameters, unknown or time-varying frequencies may be learned using methods of adaptive filtering. The resonator bandwidth can be properly adjusted with regard to the changing signal/noise ratio. Decimation procedure implemented in the DSP is linked with the waveform generation. This extended framework of signal processing enables an optimized engineering design of the multiple-light optical system with adjustable performance.

1. INTRODUCTION

Accurate and fast non-invasive optical measurement is a problem of high priority in many biomedical and other applications. A short description of the optical measurement process is as follows. An assembly of light (or laser) emitting devices (LED) triggered in a certain mode generates modulated probe signals transmitted through the investigated sample at different wavelengths. One or more photo-detectors (PD) sense the totally integrated transmitted or/and scattered light in several positions. The raw optical signals should be split in components associated with different spectral lines. The signal processing part of the apparatus completes the component separation in accordance with the LED modulation regime. Due to the apparatus complexity, commercial oximeters suffice in few, usually 2-3, wavelengths [1, 2]. Construction of advanced multiple-light systems desired, say, in glucometry is a nontrivial task that requires, among other things, a wise DSP.

2. PROBLEM ANALYSIS

Usually, LEDs operate in serial or parallel modes. In the serial mode, a particular LED is triggered over a certain period while others, during this time, are held quiet (time separation method). In the parallel mode, all LEDs are triggered concurrently, but at different rates (frequency separation method). If the number of LEDs increases, both the serial and parallel modes come into conflict with the system requirements – high access rate, noise attenuation, channel independence, etc.

Thus, in the serial mode, a longer operation with one LED restricts the access to other. Accordingly, improving the signal/noise ratio (SNR) by longer integration increases the time delay between outputs. On the second hand, the serial mode causes certain problems in signal processing. Thus, in the serial mode it is hard to differ between the signal disturbances and LED-to-LED variations. Next, due to the time separation mode, the continuous interference can not be rejected efficiently. A straightforward pre-filtering destroys the inter-channel independence and therefore is inappropriate.

Triggering LEDs in the parallel mode leads us to a classic frequency separation problem. However, there are many critical points behind this approach as well.

Note that the rate of triggering is limited by the system time constant. At the same time, since the output LED signals are non-sinusoidal waveforms they produce strong high-order harmonics. To this end, the 1st component – basic modulation rate and its corresponding second harmonic restricts the frequency interval where all other components are placed. As the number of channels increases, the inter-component distance decreases accordingly, causing coupling.

Next, due to the scale factor non-linearity, all harmonics interfere thus producing multiple sub-harmonics. There are some other noteworthy points. First, the parallel mode yields the hardware extra complexity. Second, concurrent run of LEDs reduces the dynamic range of channels. Moreover, the sensed optical intensity may vary at different wavelengths thus stressing the problem of interference between strong and weak signals. Due to all above reasons nor serial nor parallel mode is a good basis for the multiple-light optical system.

In real-life situations, severe environmental conditions substantially complicate the problem of signal recovering. The measurement is usually affected by a strong optical interference when the signal/noise ratio (SNR) reduces to 0 dB and less.

The basic idea of suggested approach is to construct a flexible optical system with diverse LEDs operation modes (rather than trivial parallel or serial modes) producing appropriate, more efficient probe signals. To this end, it is very important that the probe signal enabled by the optical part should not be restricted by the signal processing part of the system. In order to complete this task, one should develop an appropriate DSP framework allowing separation of signals composed in different modes, with different rates, over different intervals, etc.

Let us consider, for instance, a combination of parallel and serial modes. In this, say serial-parallel mode, LEDs are divided into two or more groups, each group operating in a serial mode with a certain rate. Not necessarily one LED belongs to one group. Numbers of LEDs operating in parallel or in series are parameters. Duration of the LED activity (number of cycles) is a parameter as well. With this mixed modulation mode, one has the access to a particular light intensity as soon as the corresponding LED is involved. The DSP patterns that deserve, in this context, to be mentioned are the recursive Short Time Fourier Transform (STFT) and related methods - so-called Kalman-like spectral observer (SO) and its variants [3-6].

The study presents an extended SO framework allowing non-uniform sampling and non-harmonic frequencies, concurrent retrieval of desired and rejection of undesired spectral lines, adaptive estimation of amplitudes, phases and frequencies, application of auxiliary band filters, and other options.

Table 1. Extended Spectral Observer

<u>*Design Parameters*</u>

Slow Convergence Parameter, ε_a, ε_1

Fast Convergence Parameter, γ_a, γ_1

Frequency Convergence Parameter, ρ_a, ρ_1

Forgetting Factor μ,

Fixed-Frequency Disturbances ω_d, $d=1, 2,\ldots;$

Unknown Disturbances Initial Guess ω_{u0}, $u=1, 2,\ldots;$

Modulation Rates ω_r, $r=1, 2,\ldots;$

Indices of LEDs $l=1, 2,\ldots, N;$

Indices of Harmonics $k=1, 3,\ldots;$

LED Switch Functions χ_r^l, $r=1, 2,\ldots;$ $l=1, 2,\ldots, N;$

<u>*State VectorDesignation:*</u>

x_1 *– dc (single state),* x_2 *– rate (single state),…*

x_3 *–* 1^{st} *Modulation Rate,* 1^{st} *LED,* 1^{st} *Harmonic (in-phase&quadrature pair of states),…*

x_i *–* r^{th} *Modulation Rate,* l^{th} *LED,* k^{th} *Harmonic (pair of states),…*

x_p*-* d^{th} *known-frequency disturbance* ω_d *(pair of states),…*

x_q *–* u^{th} *unknown-frequency disturbance* ω_u *(pair of states),…*

<u>*Transition Matrices:*</u>

Trend Filter (dc-rate) - $T_{tr}=\begin{bmatrix}1 & \tau\\ 0 & 1\end{bmatrix}$, *where* τ *-sampling time,*

i^{th} *Resonator for* l^{th} *LED,* r^{th} *Modulation Rate &* k^{th} *Harmonic,*

$i=i_{r,k,l}$, $r=1, 2\ldots;$ $k=1, 3,\ldots;$ $l=1,\ldots,N;$

$C_i=\cos(k\omega_r)$, $S_i=\sin(k\omega_r)$, $T_i=\begin{bmatrix}C_I & S_I\\ -S_i & C_I\end{bmatrix}$,

p^{th} *Resonator related to* d^{th} *fixed-frequency Disturbance*

$C_p=\cos(\omega_d)$, $S_p=\sin(\omega_d)$, $T_p=\begin{bmatrix}C_p & S_p\\ -S_p & C_p\end{bmatrix}$, $p=p_d$, $d=1, 2,\ldots$

<u>*Fixed Part of Integrated Transition Matrix*</u>

$T_0= T_{tr}\oplus(-1)\oplus bd(T_I, I=i_{r,k,l}, r=1, 2\ldots; k=1, 3,\ldots;$
$l=1,\ldots,N)\oplus bd(T_p, p=p_d, d=1, 2,\ldots)$

<u>*Gains of Polynomial Filter*</u>: G_{dc}, G_{rate}

<u>*Fixed Part of Gain*</u>

$G_0=[\, G_{dc}, G_{rate}, \gamma(C_i, -S_i,\ldots), \varepsilon(C_p, -S_p,\ldots)]$

$i=i_{r,k,l}$, $r=1, 2\ldots;$ $k=1, 3,\ldots;$ $l=1,\ldots,N;$ $p=p_d$, $d=1, 2,\ldots$

<u>*Initialization for n=0:*</u>

Fast Relaxation Factor $\gamma(0)=\gamma_a$

Slow Relaxation Factor $\varepsilon(0)=\varepsilon_a$

Frequency Convergence Factor $\rho(0)=\rho_a$

Unknown Disturbance Frequency: $\omega_u(0)=\omega_{uo}$, $u=1, 2,\ldots;$

<u>*Compute For Time Instant* $n=1, 2, \ldots$</u>

Current Observation Function

$h=h(n)=[1, 0, \chi_1^1, 0, \ldots, \chi_r^l, 0,\ldots,1, 0,\ldots,1, 0]$

Current State Update Function

$\chi=\chi(n)=[1, 1, \chi_1^1, 0, \ldots, \chi_r^l, 0,\ldots,1, 0,\ldots,1, 0]$

Transition Matrix of Resonator related to u^{th} *Var.-freq. Disturb.*

$C_q=\cos(\omega_u)$, $S_q=\sin(\omega_u)$, $T_q=\begin{bmatrix}C_q & S_q\\ -S_q & C_q\end{bmatrix}$, $q=q_u$, $u=1, 2,\ldots$

Integrated Transition Matrix (Updated)

$T=T_0\oplus bd(T_q, q=q_u, u=1, 2,\ldots)$

Updated Gain

$G=[G_0, \varepsilon(C_q, -S_q, \ldots)], q=q_u, u=1, 2,\ldots;$

$x(n+1|n)=Tx(n)$ *– Prediction*

$e(n)=y(n)-h(n)x(n+1|n)$ *– Prediction Error*

$x(n+1)=x(n+1|n)+\chi(n)Ge(n)$ *– State Update*

Amplitude Related to l^{th} *LED,* $l=1,\ldots,N$

(Composed from In-Phase/Quadrature and Harmonics)

$A_l=sqrt(\Sigma c_i^2+\Sigma s_i^2, i=i_{r,k,l}, r=1, 2\ldots; k=1, 3,\ldots;$

Unknown Disturbance Phase

$\varphi_q(n+1)=\arctan(c_q/s_q)+k_q\pi$, $q=q_u$, $u=1, 2,\ldots;$

k_q *is an unwrapping factor preventing higher than* π *jumps.*

Unknown Frequency Update

$\omega_q(n+1)=\rho\omega_q(n)+(1-\rho)[\varphi_q(n+1)-\varphi_q(n)]$, $q=q_u$, $u=1, 2,\ldots;$

Relaxation Factors:

$\gamma=\mu\gamma+(1-\mu)\gamma_1$, $\varepsilon=\mu\varepsilon+(1-\mu)\varepsilon_1$, $\rho=\mu\rho+(1-\mu)\rho_1$

3. PRINCIPLES OF SIGNAL PROCESSING

Hence, the processing of multiple-light optical signals comprises, in particular, 1) retrieval of the LED-related harmonic components and tracking of the time-varying amplitudes, 2) rejection of harmonic (single-tone) disturbances with unknown (in stationary conditions) or time-varying (in non-stationary conditions) frequencies, 3) rejection of low-band and narrow-band disturbances, and other tasks. An extended framework resolving this problem is sketched in Table 1.

The problem of harmonic retrieval may be viewed in the context of SO formulation. Consider a time-varying vector $\mathbf{s}=\mathbf{s}(n)=(\sigma_1,\ldots, \sigma_N)^T$, where $\sigma_i=r_i\cos(\omega_i n+\varphi_i)$ is an i^{th} sinusoid of amplitude r_i, angular frequency ω_I and phase φ_i, n - discrete time (further dropped whenever possible). Assume that one observes the signal $y=\sigma_1+\ldots+\sigma_N+v$, a sum of sinusoids corrupted by the noise $v=v(n)$. The SO outputs an $(N\times1)$-dimensional vector signal $\boldsymbol{r}$ where each term relates to a corresponding element r_i.

Each LED is linked to a particular resonator (or a group of resonators) in the SO frame. Auxiliary resonators can be involved, if necessary, for particular electrical or optical disturbances. The LED-related resonators operate in accordance with the LED ignition. A resonator associated with the active LED opens its input and updates the output. A resonator linked with the currently quiet LED locks its input and operates in a conservative mode, sustaining the constant output. A resonator associated with continuous in time interference reacts on the input irrespective of LEDs states.

To match the SO with the LEDs activity, we introduce the vector of switching functions $\boldsymbol{\chi}=[\chi_i(t)]$, $i=1,\ldots N$. The binary term $\chi_i=\chi_i(t)$ indicates 1 if the i^{th} LED is active, and 0 otherwise. This term nulls a contribution of passive LEDs in computation of the observation error and the state update, while the state propagation is performed as usual for all resonators. Introducing switching functions allows the SO be in agreement with any composed LED operation regime.

A certain part of the processing scheme is reserved for a slowly varying component, trend. The familiar SO comprises a dc term inherent from the STFT and, actually, the bias is a dominant component of the trend. However, more complicated trend filters may be incorporated, if necessary. The trend is usually described by a polynomial model comprising the dc parameter (bias), slope (rate), and, optionally, higher derivatives – acceleration and even jerk. The trend filter relying on these models is known as a 'polynomial' tracking filter [7]. Note that both the steady-state (constant-gain) polynomial filter and SO represent state-space forms of the Kalman-like predictor-corrector and can be readily aggregated. In practice, one may suffice in a simple 2nd-order trend filter.

If the resonator frequency is unknown, the SO may be further modified for adjusting the frequency parameter. In this connection, methods that deserve to be mentioned are, first, the ANF-like technique [6] and, secondly, direct computation of the phase increment [5].

Another attractive capability of the SO is the adjustable resonator bandwidth which is a function of the SNR.

To eliminate a disturbance with narrow band or another complex spectrum, the frequency-sampling method may be applied in order to derive the proper band filter. This filter can be incorporated into the same unified SO framework with the help of auxiliary resonators matching the corresponding frequency band.

Basic steps of the extended SO are shown in Table 1, while other are omitted due to the space limitation. More detail can be found in [8].

4. SYSTEM DESIGN EXAMPLE

As is sketched in Fig. 1, the optical system comprises a group of LEDs with presumed wavelengths λ_1, λ_1,… Each LED is triggered at a certain rate thus producing periodic, nearly square however non-ideal waveforms. All light waveforms are transmitted through a sample. The resulting light intensity is sensed by a PD, amplified and digitized at a high (250-300 kHz) sampling rate. The resulting waveform is substantially distorted by the limited channel bandwidth.

In order to recover LED-related components, one should take into account that the LED-induced waveform is asymmetric and has a complex spectral content with significant higher order harmonics. However, application of a comb filter with multiple resonators is not practical due to extra computation. In contrary, a goal is to reduce the sampling rate before the SO is applied. To this end, the SO is coupled with an appropriate decimation procedure. A basic requirement to the latter is that the pulse shape distortion doesn't affect spectral lines of interest.

Fig. 1 presents a flowchart of the multiple-LED system operating in a combined serial-parallel mode, while the signal transform is sketched in Fig. 2. The generator provides two pulse sequences $\mathbf{F_1}$ and $\mathbf{F_2}$, with different pulse rates. Each of these two sequences is split into N subsequences $\mathbf{F_1^1}$, $\mathbf{F_1^2}$,…, $\mathbf{F_1^N}$ and $\mathbf{F_2^1}$, $\mathbf{F_2^2}$,…, $\mathbf{F_2^N}$, respectively.

First, the N LEDs should be triggered by the pulses $\mathbf{F_1^1}$, $\mathbf{F_1^2}$,…, $\mathbf{F_1}^N$, respectively. At the same time, another serial mode regime with different rate (the pulses $\mathbf{F_2^1}$, $\mathbf{F_2^2}$,…, $\mathbf{F_2}^N$) should be applied to the same N LEDs. Thus, the 1st LED with the wavelength λ_1 is to be driven by the superposition of $\mathbf{F_1^1}$ and $\mathbf{F_2^1}$, the superposition of $\mathbf{F_1^2}$ and $\mathbf{F_2^2}$ drives the 2nd LED λ_2, etc.

The processing starts with the decimation step. Since signals run in turn, over short periods, conventional anti-aliasing filters with usually long transient are not applicable. The principle we follow is to choose a modulation rate such that higher harmonics coincide, after aliasing, with corresponding lower harmonics, thus keeping distances between basic spectral lines unchanged.

Suppose, for instance, that the initial sampling rate is 250 kHz and the desired sampling rate for the SO is 25 kHz. One should choose modulation rates that agree with the above principle. On the other hand, the modulation rate is restricted from above due to the system bandwidth. With too high modulation rate, the pulse transients of consequent LEDs may intersects. There are two modulation rates, particularly, 3.125 kHz and 2.5 kHz that agree with these requirements. Decimation now may be completed by integration over each 10 samples. Regarding the 2.5 kHz modulation, it reduces the rate from 100 samples per period to the 10 samples per period. Regarding the 3.125 kHz, it reduces the rate from 80 samples to 8 samples per period. After decimation, the 2.5 kHz signal comprises 1st and 3rd harmonics, while 5th harmonic coincides with the Nyquist frequency. Similarly, 3.125 kHz signal holds 1st and 3rd harmonics. Even harmonics caused by the LED pulse asymmetry are not of interest.

After the first decimation stage, the SO sampling rate reduces to the 25 kHz. The resonator R_i in Fig. 1 associates with the two-component state $x_i=(c_i, s_i)^T$ in Table 1. The output amplitude A_i is received from in-phase and quadrature components.

Each recovered signal $\boldsymbol{R_r^l}$ (r=1,2; l=1,…, N) needs two resonators, for the 1st and the 3rd harmonics, respectively. Each LED is triggered by two subsequences, and therefore each channel needs four resonators, two for the modulation rate 3.125 kHz, and another two - for 2.5 kHz. Aggregating four resonators provides a total output for the corresponding optical channel.

In Fig. 2, resonators outputs $\boldsymbol{R_1^1}$ and $\boldsymbol{R_2^1}$, associated with pulses $\boldsymbol{R_1^1}$ and $\boldsymbol{R_2^1}$, respectively, shown to compose the resulting output $\boldsymbol{A^1}$, resonators $\boldsymbol{R_1^2}$ and $\boldsymbol{R_2^2}$ compose the resulting output $\boldsymbol{A^2}$, etc. Thus N desired outputs are obtained.

5. CONCLUDING DISCUSSION

The study presents an extended DSP framework combining a spectral observer, trend filter, band-pass filter and other tools necessary for processing of optical signals in non-invasive biomedical technologies - oximetry, glucometry, etc. The resulting filter is convenient for implementation and was realized in a standard TMS320C67x processor.

The optical system may be readily reconfigured to meet varying environmental conditions and applications by sole adjustment of several programmable parameters, such as choice of parallel and serially triggered LEDs, LED activity duration, modulation rates, etc. An optimized engineering design of the system may be thus completed wrt given performance criteria.

With the help of this approach the optical system resolves a large quantity of optical signals with high accuracy and speed. In particular, for 10 to 15 optical channels with relatively 12.5 to 6.25 Hz output bandwidth, the system provides 60-50 dB damping ratio for the white noise, and nearly 40-60 dB attenuation for the 100 Hz light interference. The interaction between optical channels is less than 100 ppm.

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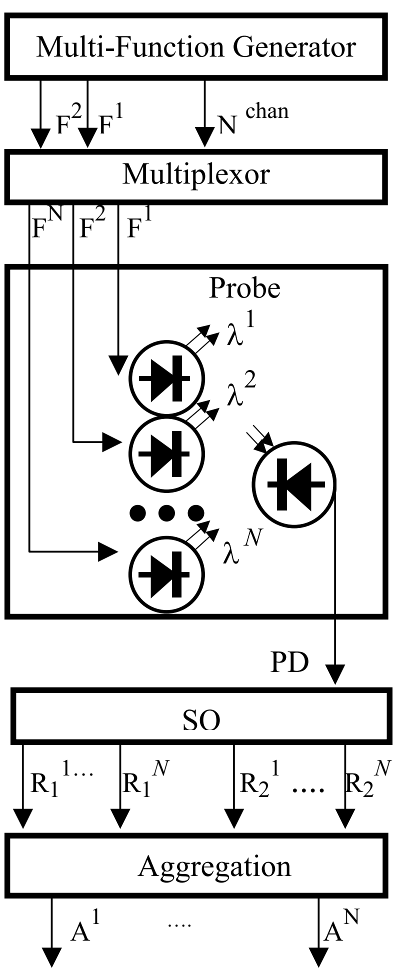

Fig. 1. System flowchart.

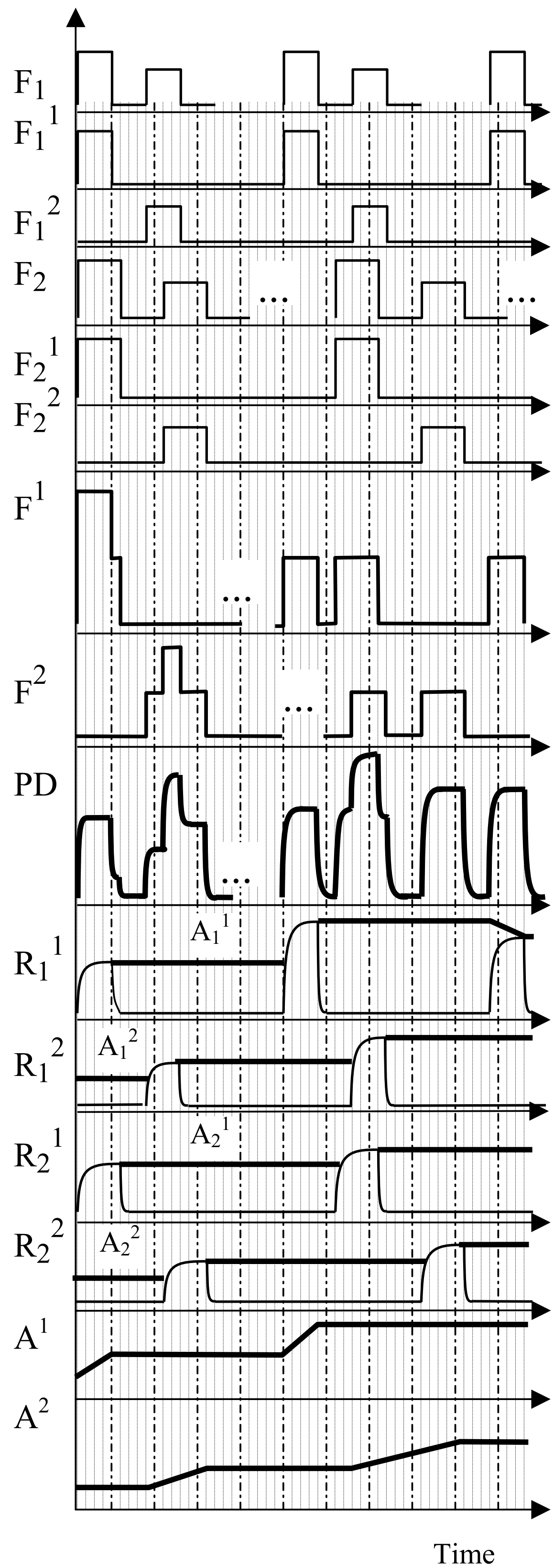

Fig. 2. Signal transform.