Monitoring and Processing of the Pupil Diameter Signal for Affective Assessment of a Computer User

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Abstract. The pupil diameter (PD) has been found to respond to cognitive and emotional processes. However, the pupillary light reflex (PLR), is known to be the dominant factor in determining pupil size. In this paper, we attempt to minimize the PLR-driven component in the measured PD signal, through an Adaptive Interference Canceller (AIC), with the H^{∞} time-varying (HITV) adaptive algorithm, so that the output of the AIC, the Modified Pupil Diameter (MPD), can be used as an indication of the pupillary affective response (PAR) after some post-processing. The results of this study confirm that the AIC with the HITV adaptive algorithm is able to minimize the PD changes caused by PLR to an acceptable level, to facilitate the affective assessment of a computer user through the resulting MPD signal.

Keywords: Pupil diameter (PD), Pupillary light reflex (PLR), Pupillary affective response (PAR), Adaptive Interference Canceller (AIC), H^{∞} time-varying (HITV) adaptive algorithm.

1 Introduction

Affective Computing, defined as "computing that relates to, arises from, or deliberately influences emotions" by Picard in 1997 [1] requires computers to have the ability to remain aware of their users' affective states. Therefore, the affective assessment of the computer user has been considered as one of the key challenges to overcome for improvement of the relationship between human and computers. This challenge has been addressed, among other approaches, through the processing of a variety of physiological signals from the computer users, such as the Galvanic Skin Response (GSR), the Blood Volume Pulse (BVP), etc. We are currently studying the possibility of analyzing pupil diameter (PD) variations in the computer user for the detection of affective changes.

The human pupil is the variable-size opening in the iris of the eye, through which light passes to the retina. The size of pupil is known to be controlled by two opposing sets of muscles in the iris, the sphincter and dilator pupillae, which are governed by the sympathetic and parasympathetic divisions of the Autonomic Nervous System (ANS) [2]. Traditionally, light intensity has been considered as the major determinant of the pupillary response, through the Pupillary Light Reflex (PLR). However, other

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psychological factors controlling pupil size, such as emotional processes have recently been investigated. For example, in 2003, Partala and Surakka found, using auditory emotional stimulation, that the pupil size variation can also be seen as an indication of affective processing during human-computer interaction [3]. Therefore, in this paper, we focus our study on monitoring and processing the pupil diameter (PD) signal for the affective assessment of a computer user.

To achieve the required separation of the PLR-driven component from PD changes due to Pupillary Affective Responses (PAR) we propose an Adaptive Interference Canceller (AIC), which is known to be able to remove an unwanted interference component *z(k)* that pollutes a measured signal *s(k)* using an independent measurement of the interference *n(k)* [4] (See Figure 1). The core portion of this AIC system is an Adaptive Transversal Filter (ATF), which performs the adaptive algorithm to implement the function of interference canceling. To ensure a successful noise removal from the AIC, it is important to select an adaptive algorithm that possesses good robustness properties. The H^{∞} adaptive algorithm, introduced in robust control theory, is an attempt at addressing this need, with features that are useful in safeguarding against the worst-case of model uncertainties and makes no assumption on the (statistical) nature of the signals [5].

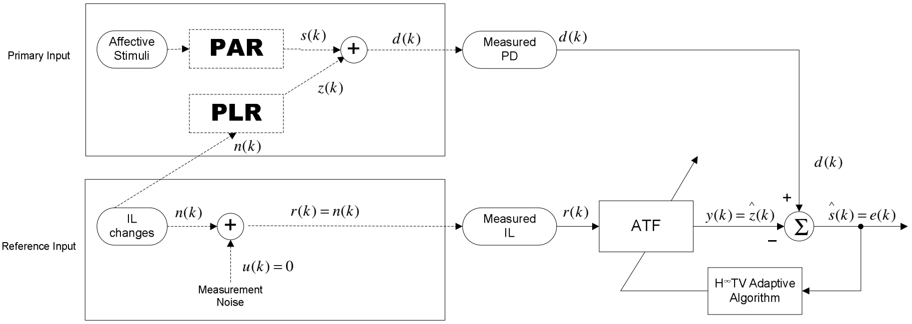


Fig. 1. Adaptive Interference Canceller (AIC) Block Diagram

Thus, we propose to use an H^{∞} –based adaptive technique, namely the H^{∞} time-varying (HITV) algorithm, in the Adaptive Interference Canceller for the removal of the PLR-driven component from the pupil diameter variation. Our intent is to use the output of the AIC, the Modified Pupil Diameter (MPD), further refined by additional processing (median evaluation of a sliding window), to indicate the occurrence of affective changes (e.g., onset of stress) in the computer user.

2 Methods

2.1 AIC Overview

A basic AIC block diagram is illustrated in Figure 1, above. The signal of interest, polluted with an uncorrelated noise signal, is transmitted over the top channel, and constitutes the primary input to the AIC. The bottom channel receives a signal, which is uncorrelated with the signal of interest, but correlated with the interference, constituting the reference input. The output of AIC is expected to provide a signal where the correlated interference has been removed.

As described in the previous paragraph, the key equations describing the AIC are:

Primary Input: $$d(k) = s(k) + z(k) \tag{1}$$

Reference Input: $$r(k) = n(k) + u(k) \tag{2}$$

Output: $$e(k) = d(k) - y(k) = d(k) - \hat{z}(k) = \hat{s}(k) \tag{3}$$

where,

- ✓ *s(k)* is the signal of interest (PD- driven by PAR);
- ✓ *z(k)* is the interference in the primary sensor (PD- driven by PLR);
- ✓ *n(k)* is the actual source of the interference (Illumination changes);
- ✓ *u(k)* is the measurement noise. (In this study, *u(k)* is assumed to be zero);

In the AIC system, the core element is an adaptive transversal filter (ATF), where the reference signal *r(k)* is processed to produce an output $y(k) = \hat{z}(k)$ that is an approximation of *z(k)*. The state space model of the ATF is given by [5]:

$$w(k+1) = w(k) + \Delta w(k) \tag{4}$$

$$d(k) = r(k)^T w(k) + v(k) \tag{5}$$

$$z(k) = r(k)^T w(k) + \upsilon(k) \tag{6}$$

$$v(k) = s(k) + \upsilon(k) \tag{7}$$

In these equations,

- ✓ *w(k)* = system state vector, is the ATF coefficient vector of size $m \times 1$ (m is the order of ATF);
- ✓ *d(k)* = measurement sequence, is the observed pupil diameter(PD) signal.
- ✓ *z(k)* = sequence to be estimated
- ✓ $\Delta w(k)$ = process noise vector, represents the time variation of the ATF weights *w(k)*.
- ✓ *v(k)* = measurement noise vector, includes *s(k)* (PD- driven by affective changes) and model uncertainties $\upsilon(k)$.
- ✓ $r(k) = [r_k, r_{(k-1)}, \ldots\ldots, r_{(k-m+1)}]^T$ is the interference vector of size $m \times 1$

As shown in Figure 1, for this study we define the primary input of the AIC as the recorded pupil diameter signal, which is composed by the signal of interest *s(k)* (PD- driven by PAR) and the interference *z(k)* (PD- driven by PLR). Although, the reference input comprises both the actual source of the interference *n(k)* (actual illumination changes) and the measurement noise *u(k),* under the assumption that the measurement noise is negligible, an independent measurement of illumination in the neighborhood of the eye of the subject (IL) is used as the reference input. We expect the adaptive transversal filter (ATF) to emulate the transformation of the illumination variations to pupil diameter changes, which would convert the noise *n(k)* into a close-enough replication of the PLR-driven components of PD (the output *y(k)*). Therefore, the error, *e(k)* (Modified Pupil Diameter), would be the estimation of the desired signal *s(k)*, i.e., the PD variations due exclusively to affective changes (PAR).

2.2 H^{∞} Time-Varying Adaptive Algorithm

In this study, the adaptive algorithm we applied to the Adaptive Interference Canceller system is the H^{∞} time-varying (HITV) adaptive algorithm, which aims to remove the noise from the recorded signal by adaptively adjusting the impulse response of the ATF. The robustness of this HITV algorithm is derived from its minimization of the maximum energy gain from the disturbances to the estimation errors with the following solutions [6]:

$$\tilde{P}^{-1}(k) = \mathrm{P}^{-1}(k) - \varepsilon_g^{-2}\mathrm{r}(k)\mathrm{r}^T(k) \tag{8}$$

$$g(k) = \frac{\tilde{\mathrm{P}}(k)\mathrm{r}(k)}{1 + \mathrm{r}^T(k)\tilde{\mathrm{P}}(k)\mathrm{r}(\mathrm{k})} \tag{9}$$

$$\hat{w}(k+1) = \hat{w}(k) + g(k)(y(k) - \mathrm{r}^T(k)\hat{w}(k)) \tag{10}$$

$$P(k+1) = [P^{-1}(k) + (1 - \varepsilon_g^{-2})r(k)r^T(k)]^{-1} + \gamma_0 \tag{11}$$

$$P(0) = \eta I = \Pi_0\,,\ \Upsilon_0 = \rho I \tag{12}$$

Here, $g(k)$ is the gain factor; ε_g , η and ρ are positive constants. Note that ρ reflects a priori knowledge of how rapidly the state vector $w(k)$ varies with time, and η reflects the a priori knowledge of how reliable the initial estimate available for the state vector $w(0)$ is.

3 Experiments

3.1 Subjects

We have collected data from twenty-two volunteer students who have completed the protocol described below. All the subjects reported to have normal color vision and had experience using computers. This paper presents results achieved through the processing methods proposed on a subset of the subject pool recorded to date.

3.2 Task

In order to observe the response of pupil diameter changes to affective stimuli, the “Stroop Color-Word Interference Test”, implemented as a flash program [7], was used to elicit mild mental stress in the participating subjects during the experiment.

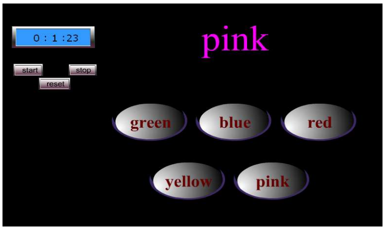


Fig. 2. Sample of Stroop Test Interface

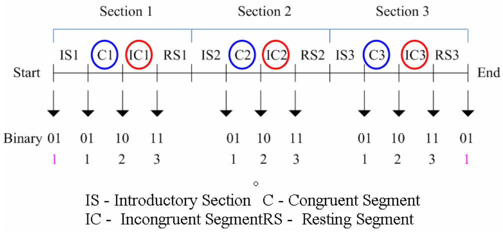


Fig. 3. Stimuli schedule of the Stroop Test

In the test, a word presented to the subject designates a color that may or not match the font of the word. The subjects are instructed automatically by the program to select (out of 5 possible choices) the screen button that indicates the font color of the word presented, by clicking on it (An example, showing the appearance of the test interface is shown in Figure 2).

The stimuli schedule of the test in the experiment is shown in the Figure 3. The complete protocol is composed of three consecutive sections. In each section, there were four segments.

- ✓ 'IS' – the Introductory Segment to let the subject get used to the task environment;
- ✓ 'C' – the Congruent segment of the Stroop Test, in which the subject was asked to click the on-screen button naming the font color of a word that correctly spelled the font color being displayed;
- ✓ 'IC' – the Incongruent segment of the Stroop Test in which the subject was asked to click the on-screen button naming the font color of a word that spelled the name of a different color;
- ✓ 'RS' – is a Resting Segment to let the subject relax for some time.

The incongruent Stroop segments (IC) were expected to elicit mild mental stress in the subject, according to previous research found in the psychophysiological literature [8]. In contrast, the congruent Stroop segments (C) were expected to allow the subject to continue in a relaxed state. The binary numbers shown in Figure 3 represent the demultiplexed output of the stimulus generator, which is used to insert the corresponding values (1, 2, 3) in the event channel of the PD data file, and the corresponding time marks in the illumination measurement data, recorded simultaneously.

3.3 Instruments

In this study, a desk-mounted eye tracking system (TOBII T60) was used to measure the pupil diameter signals from both eyes of the subjects at 60 samples/sec. The average ((L+R)/2) was recorded as the "Measured PD" signal, which corresponds to *d(k)*, in Figure 1. Simultaneously, the illumination intensity level present in the area around the eyes of the subjects was recorded by a system built for that purpose. This system is composed by a BS500B0F photo-diode (Sharp), placed on the forehead of the subject and connected to an amplification circuit to provide an analog output voltage that is proportional (~0.0043 v/Lux) to the illumination intensity level [9]. The "Measured IL" signal, r(k), shown in Figure 1 was finally provided by sampling the analog output of the luminance meter at the frequency of 360 Hz with a Data Acquisition (DAQ) System (PCI-DAS6023 board from Measurement Computing Co.)

3.4 Procedure

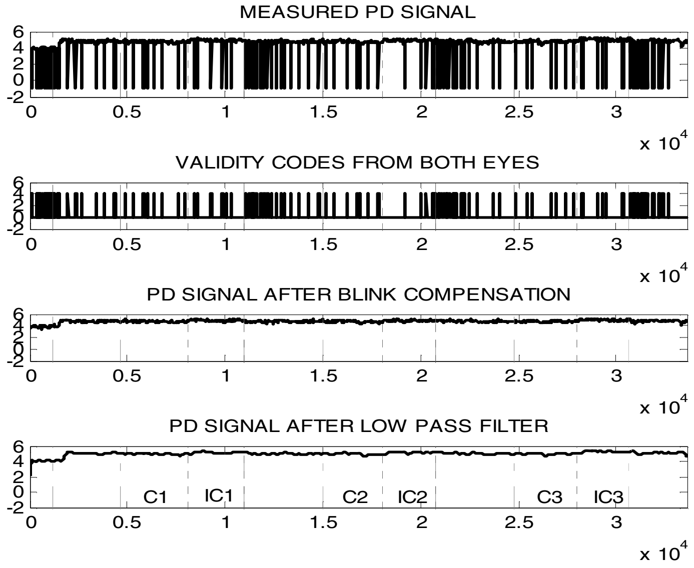
In our experiments, participants were asked to remain seated in front of the TOBII screen, interacting with the "Stroop Test" for about 30 minutes, while wearing a head band with the photo-diode. During that time, all the normal lights in the room were kept on, but an additional level of illumination provided by a desk lamp placed above the eye level of the subject was switched ON and OFF, alternatively, at intervals not previously known by the subject, using a dimmer. This was done to repeatedly introduce passages of high and low illumination in the experiment, which would trigger the pupillary light reflex.

4 Results

Before its application to the adaptive interference canceller, the recorded pupil diameter signal is pre-processed by a blink-removal algorithm implemented in MATLAB, which is able to:

1. Detect the PD data interruptions due to eye blinks (identified as a value of "4" in the validity code provided by the TOBII system);
2. Compensate the missing data by linear interpolation.
3. Filter out the blink responses through a low pass, 512th order FIR filter designed for a cutoff frequency 0.13Hz.

Figure 4 illustrates the stages of the blink-removal process on data collected from subject 13.



MEASURED PD SIGNAL

VALIDITY CODES FROM BOTH EYES

PD SIGNAL AFTER BLINK COMPENSATION

PD SIGNAL AFTER LOW PASS FILTER

Fig. 4. PD Signal Before & After Blink-Removal

The PD signal obtained after blink-removal is applied to the AIC system as the primary input signal *d(k)*, and the reference input *r(k)* is the simultaneously measured illumination intensity level signal, which is down-sampled from 360Hz to 60 Hz to share the same sampling rate with the PD signal. A MATLAB program was created to apply the HITV adaptive algorithms for the ATF with 120 weights and the parameter settings of $\eta = 0.001$, $\varepsilon_g = 2.0$ as well as a time-varying parameter ρ, changed according to the IL value to enable the AIC system to have a quicker response when there is a sudden increase in IL. The output of the AIC, the MPD, is shown in the bottom plot of Figure 5. This signal is further processed as described below to become a useful indicator of pupillary affective response in the subject.

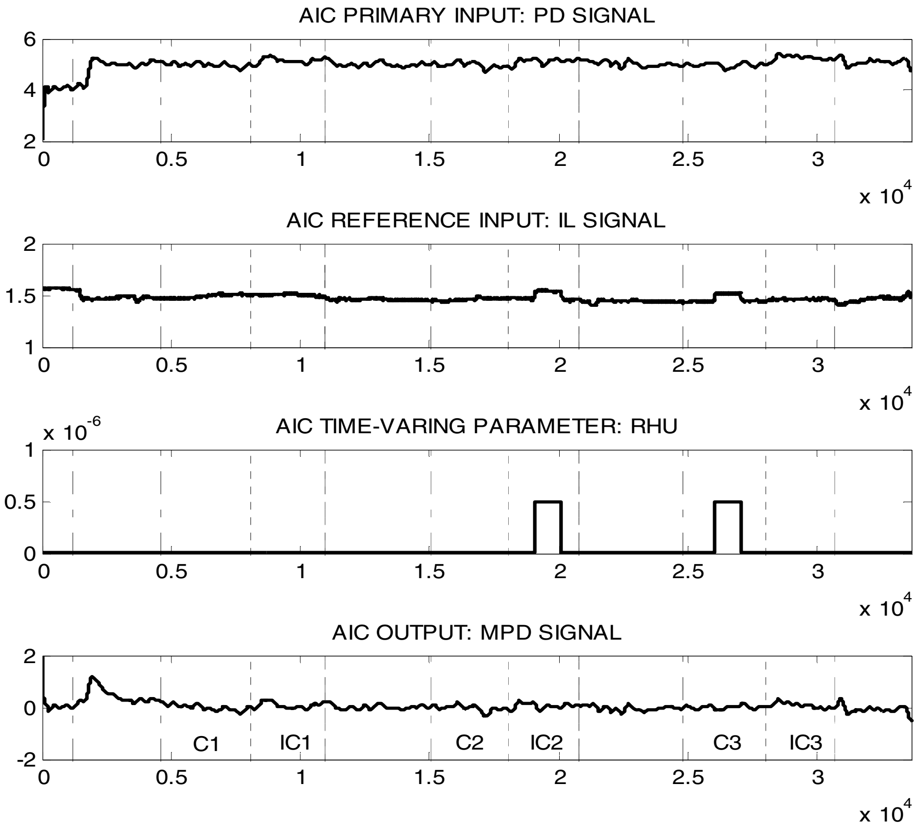


Fig. 5. AIC Implementation with HITV Algorithm

The affective state of "Stress" is expected to cause a dilation of the pupil [2]. Therefore, the negative portions of the MPD signal, are zeroed to isolate significant MPD increases, which indicate the emergence of stress in the subject. The result of applying this non-negative restriction to the MPD signal is shown in the bottom panel of Figure 6.

A sliding window with a width of 1200 samples is applied throughout the non-negative MPD signal to calculate the median value within each window. The effect of this process on both the original PD signal and the non-negative MPD signal is compared in Figure 7.

In this figure, it is clear that the significant increases that have been isolated in the processed MPD signal correlate closely with the occurrence of IC segments, regardless of the presence of higher illumination passages during segments IC2 and C3. It should also be noted that the same post-processing operated on the PD signal obtained directly from the eye gaze tracking system does not set apart the IC segments as clearly.

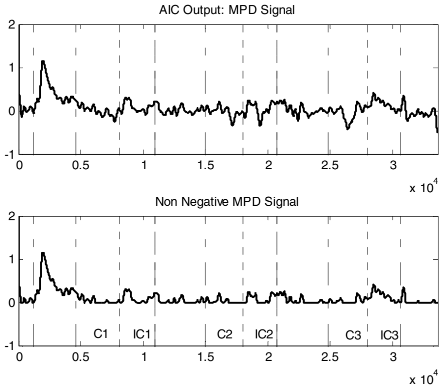


Fig. 6. MPD Signal Non Negative Processing for Stress Indication

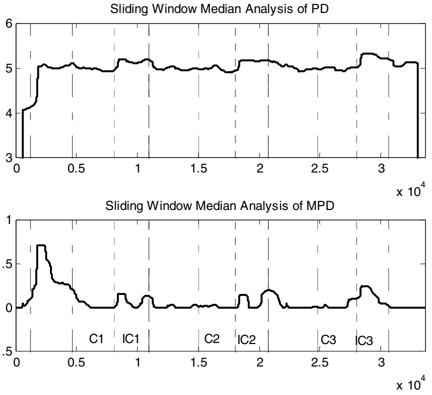


Fig. 7. Comparison of Sliding Window Median Analysis on PD & MPD

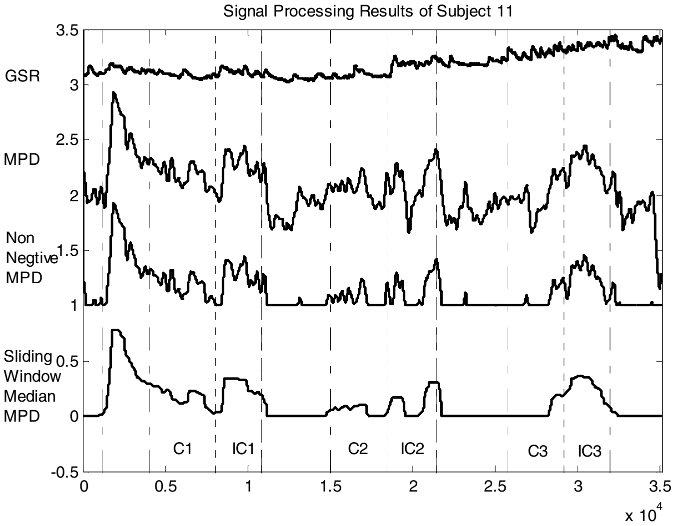


Fig. 8. Signal Processing Results of Subject 11

A similar result is observed for data collected from Subject 11, as shown in Figure 8, where the 3 top signals (GSR, which was recorded simultaneously, MPD and Non-negative MPD) have been shifted up to make the display clear. In this case, also, the most significant increases of the bottom trace, after the initial adaptation that precedes segment C1, occur during the incongruent segments (IC1, IC2 and IC3).

This figure shows the appearance of Skin Conductivity Responses (SCRs) and overall elevation of the GSR signal during the incongruent segments. Furthermore, the bottom plot (the result of the proposed post-processing) also shows significant increases during IC1, IC2 and IC3, with minimal output on the other segments after the initial adaptation.

5 Conclusions

This study implemented an H^{∞} time-varying adaptive algorithm in an Adaptive Interference Canceller to discount the influence of Pupillary Light Reflex from a measured PD signal, so that the output of the AIC, the MPD, with the application of a non negative constraint and sliding window median analysis, can be used as an indicator of Pupillary Affective Responses due to, for example, subject stress. This indicates that this approach might be useful for the affective assessment of a computer user, even in the presence of illumination changes. A comparison of this result with the outcome obtained by applying the same post-processing directly to the recorded pupil diameter signal, points out the advantage of the adaptive implementation, which output relatively more distinctive increases when the incongruent Stroop segments occurred. Data from other subjects who participated in our experiment have revealed similar results. These outcomes, therefore, encourage the continued exploration of adaptive processing algorithms applied to pupil diameter signals, as a non-invasive mechanism to achieve affective assessment of computer users in ordinary environments.

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