TWO COMPARTMENT FUSION SYSTEM DESIGNED FOR PHYSIOLOGICAL STATE MONITORING

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Abstract- **A two-compartment fusion system designed to reduce high rates of false alarm (FAR) in single channel monitoring systems was tested with physiological data from pilots exposed to high +Gz forces on a human centrifuge. The first compartment expands input signals into time-frequency domain, where transient changes are captured by wavelet coefficients in frequency ranges of interest. The second compartment optimally combines local decisions of various statistics using a unifying operation rule regardless of individual subject physiology and channel features. Three channels were used to measure respiration, blood pressure, and electroencephalogram under various high performance aircraft maneuver profiles: rapid onset run (ROR) to a fixed plateau, gradual onset run (GOR) at 0.1 Gz per second onset, and simulated aerial combat (SACM) profiles. Pilots sometimes perform anti-G straining maneuvers (AGSM) against the blood pressure drop at head level for greater tolerance. Signals were simultaneously processed to decide the presence of such AGSM. Significant reductions of FAR when detecting AGSM by signal fusion were achieved in our experiment (10~38% during ROR /GOR, 25~35% during SACM, and 21~36% overall), when compared to single channel monitoring. This implies that our approach is very promising and system performance can be enhanced even with poor quality signals.**

***Keywords*– Physiological monitoring, wavelet transform, data fusion, G force**

I. INTRODUCTION

The assessment and evaluation of the physiological state of patients and human experimental volunteer subjects is of great importance and interest to physicians and scientific investigators. For example, this is especially important in monitoring levels of anesthesia in the operating room or the state of consciousness of human volunteers in experiments involving very high accelerative forces [1, 2].

The evaluation of physiological state is generally based on the results from a single data channel such as blood pressure or electroencephalogram. These are either monitored visually or the physician or researcher relies on an automatic alarm triggered by a parameter value that is out of the normal expected range. A significant problem with such methods is that there is often a high false alarm rate (FAR) due to such things as sensor movement, physiological parameter variability, and electrical signal noise [2].

In order to overcome these difficulties we have used multiple sensors measuring different physiological parameters, each of which can be used to detect the event of interest. We evaluate the physiological state measured by each sensor and then fuse these measurements to generate a single result whose FAR is much smaller than that encountered from the individual channels [3-6].

In such a system the individual sensors generate data that is processed and yields a “local” result with relatively high FAR. These “local” results are then combined using an optimal unifying rule that then gives a “global” evaluation of the human’s physiological state with reduced FAR. Such a data fusion system generally relies on identical sensor characteristics, identical parameter statistics, linear system characteristics, and stationary signals. The difficulties arising in determining an optimal unifying rule for a data fusion system for different physiological data channels include: different types of physiological sensors have different physical characteristics, physiological signals are typically non-stationary, different physiological signals have different statistical characteristics.

In this paper, we designed a two-compartment data fusion system for physiological signals which gives “global” results with greatly reduced FAR when compared with “local” results. This was accomplished by modifying conventional data fusion methods based on a unifying operation rule to accommodate the behaviors of complex biological signals.

II. DATA FUSION SYSTEM

A two-compartment data fusion system is shown in Fig. 1. The first compartment contains discrete wavelet transforms (DWT) to capture the complex behaviors in the input signals, S_i. Here, transient and irregular features are efficiently captured. The second compartment is the data fusion center (DFC) where wavelet-based local decisions, D_i are combined by a unifying optimal operation rule regardless of individual physiology and channel features.

Wavelet transforms decompose signals into time-frequency domain, where frequency characteristics and temporal locations of particular features can be highlighted [7].

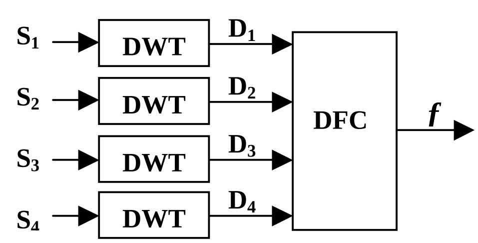

Fig. 1. Block diagram of data fusion algorithm; Si : input channel data, D_i : local decisions, and f : global decision

The wavelet transform of input signal $s(t)$ is defined as the inner product of $s(t)$ and the mother wavelet $\psi_{j,k}(t)$:

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25OCT2001	N/A	-

Title and Subtitle Two Compartment Fusion System Designed for Physiological State Monitoring	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) School of Biomedical Engineering, Science and Health Systems and Department of Electrical and Computer Engineering Drexel University, Philadelphia, USA	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes Papers from the 23rd Annual International Conference of the IEEE ENgineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom., The original document contains color images.	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 4	

$$Ws(j,k) = \langle s(t), \psi_{j,k}(t) \rangle \quad (1)$$

where j is the scale, k is translation parameter, and

$$\psi_{j,k}(t) = \frac{1}{\sqrt{j}} \psi\left(\frac{t-k}{j}\right). \quad (2)$$

This transform yields a set of wavelet coefficients $Ws(j,k)$ by focusing on specific locations on the signal containing peaks and transients in the signal. The powers of wavelet coefficients are then computed at each frequency scale and combined into a single value of power

Scales showing salient features were combined with predetermined weights. The combined powers are used to make local decisions (+1, -1) at each input channel. Local system performance at a threshold (τ_i) is determined by the graph of false alarm (P_{Fi}) vs. detection probability (P_{Di}) and is called the receiver operating characteristic (ROC).

Conventional data fusion systems use detection and estimation theory [3,4] to: 1) reduce the volume of data, 2) determine optimal thresholds for local sensors, 3) combine local decisions for optimal global decisions, and 4) couple optimal local thresholds with optimal fusion algorithms. These methods are based on significant constraints that include the following assumptions: identical signal statistics, identical detection thresholds, equal numbers of observations for each channel, and identical sensor characteristics.

Our primary goal is to optimally operate the data fusion system with a fixed fusion rule and to circumvent the above assumptions that do not fit a multi-channel physiological monitoring system. Thus, in this study, a minimum error criterion (MEC) defined as log-likelihood ratio test is employed to determine a fixed fusion rule, [8]:

$$f(D_1, D_2, ..., D_N) = \begin{cases} +1, & if\ \omega_0 + \sum_{i=1}^{N} \omega_i D_i > 0 \\ -1, & otherwise \end{cases} \quad (3)$$

where optimum weights (ω_i) for N local sensors are defined as a function of local decisions and local performance indices (P_{Fi} and P_{Di}), and global decision f is made by comparing global thresholds;

$$\omega_0 = log \frac{P(H_1)}{P(H_0)} \quad (4)$$

$$\omega_i = log \left(\frac{P_{D_i}}{P_{F_i}}\right)^{\frac{|D_i|+D_i}{2}} \left(\frac{1-P_{F_i}}{1-P_{D_i}}\right)^{\frac{|D_i|-D_i}{2}} \quad (5)$$

where: $D_i = \pm 1$, $P_{F_i} = P_{F_i}(\tau_i)$, and $P_{D_i} = P_{D_i}(\tau_i)$.

When the global threshold is greater than zero, the global decision of +1 (Yes) is made, otherwise we made -1 (No) decision (Since we assume $P(H_0)$ is equal to $P(H_1)$, ω_0=0). The system performance at each local detector is directly related to that of the DFC. Therefore optimal couplings of local thresholds needs to be found along with the strategy for optimal operation of the DFC.

III. APPLICATION

Experimental Protocols

Physiological signals were acquired from human centrifuge experiments conducted at the Naval Air Warfare Center in Warminster, PA. Human subjects were exposed to +Gz (head-to-toe) forces in the form of: gradual onset rates of acceleration (GOR) that increased at 0.1 +Gz/sec., rapid onset rates of acceleration (ROR) to a fixed high +Gz plateau level for 15 sec., and simulated aerial combat maneuvering profiles (SACM) that approximated actual combat flying scenarios. Subjects were asked to determine how their visual field was effected by monitoring LED's placed in the centrifuge gondola at 15^o increments from a central LED. If a subject's visual field was reduced to 60^o or they had greater than 75% overall loss of vision, subjects were asked to initiate an anti-G straining maneuvering (AGSM) against the head level blood pressure drop to increase their peripheral vision. During these experiments the subject's respiration pattern (R), blood pressure (BP), and electroencephalogram (EEG) were recorded. The object of our study was to automatically determine when subjects were performing the AGSM.

Figure 2 shows a set of recordings from one experiment. The +6 Gz ROR acceleration profile is shown in the first row of Fig. 2 as a source of stimulation. The second, third, and fourth rows are the physiological responses R, BP and EEG. Pilots initiate the AGSM just before the onset of +6 Gz by quick inspiration, general muscular tensing, and breath holding. This is repeated every 3 seconds in order to elevate the BP until the G stress goes off. These effects can be seen

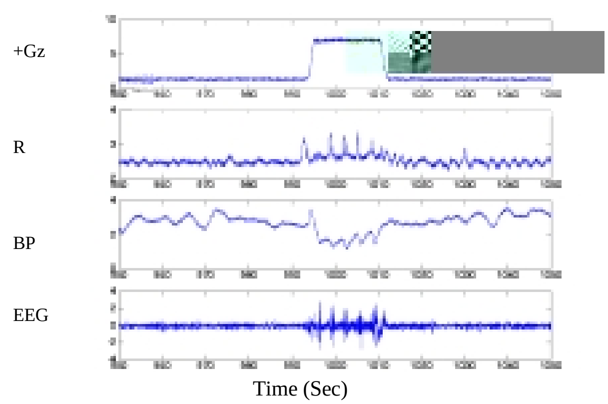

Fig. 2. Stimulating +Gz force and physiological responses with anti-G straining maneuver (AGSM): respiration (R), blood pressure (BP), and electroencephalogram (EEG).

in both the respiratory signal, blood pressure, and EEG. Six human volunteers performed a total of 103 respiratory straining maneuvers under high G stress. The presence of AGSM was monitored by video tape, and scored by research personnel.

Multi-Sensor Signal Processing

The three physiological data channels were input to the first compartment of the data fusion system. The time-frequency behavior of the signals was determined by the DWT blocks. Figure 3 shows 4 repetitions of ROR acceleration stimuli during which the subject performed an AGSM. The AGSM's were detected in each of the physiological data channels to a lesser or greater degree by the increase in wavelet coefficient powers.

Local decisions are made on the basis of thresholds, which will give optimal system performance at the DFC. Since the statistics at local sensors are different from each other, the following operation rules were used to determine local thresholds: 1) probability of detection equal to 1.0 regardless of false alarm at local sensors, 2) thresholds coupling is chosen to minimize false alarms with 100 % detection probability. This rule was applied to each sensor and from it the system performance at the data fusion center was evaluated when global decision was made as compared to fusion thresholds.

Local and global decisions under both ROR and GOR stress are illustrated in Fig. 4. The first row shows a series of 4 ROR stimuli followed by a GOR stimulus. Local decisions at the output of the first compartment are shown in the next three rows. These results are inserted into the second compartment, where global decisions (f) are made by decision fusion as shown in the fifth row. The global threshold (GT) is shown in the last row. It is clearly seen that false alarms at local detectors are greatly reduced by the fusion method, and thus enhance the system reliability. Statistical evaluations have been made to validate the data fusion system performance.

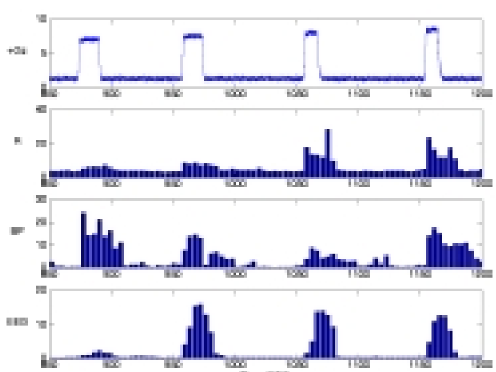

Fig. 3. Linearly combined powers of wavelet coefficients at local sensors under rapid onset +Gz run (ROR)

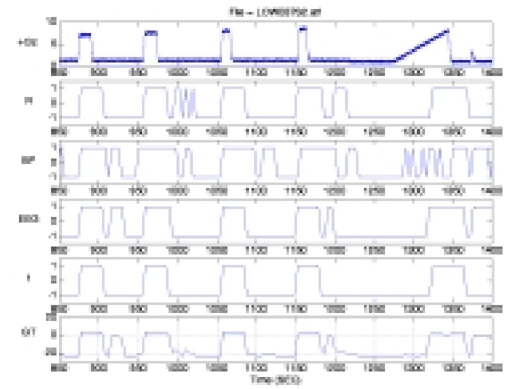

Fig. 4. Local decision and fusion decision (*f*) at the DFC with global threshold (GT)

In addition, the system performance at individual channels and fusion center is described the ROC curve as illustrated in Fig. 5. The area under this curve indicates the system performance. It is clear that the fusion system shows better performance, when compared the local system performance.

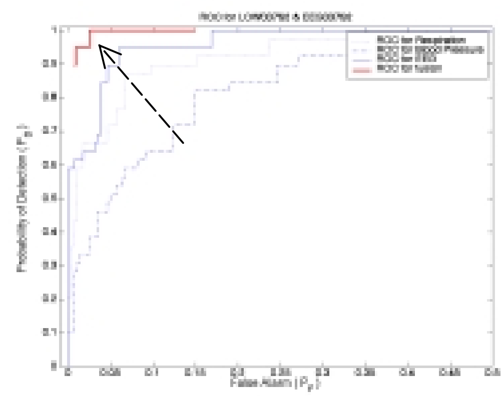

Fig. 5. Receiver operating characteristics (ROC) at local detectors and fusion center under +Gz stress

IV. RESULTS AND DISCUSSION

False alarm rates for detecting AGSM are shown in TABLE I for each of the three local detectors and for the DFC. FAR for the BP sensor was 41.69 %, for the R sensor 31.66 % and for the EEG sensor 27.01 %, whereas the FAR for the DFC was only 5.85 %. The DFC decreased the FAR over the BP sensor by 35.84 %, over the R sensor by 25.81 % and over the EEG sensor by 21.16 %, thus showing greatly improved system performance.

TABLE I

FALSE ALARM RATES AT LOCAL DETECTORS AND AT DATA FUSION CENTER (DFC)

BP	**R**	**EEG**	**DFC**
41.69 %	31.66 %	27.01 %	5.85 %

The case of defective sensors was also investigated by removing one sensor at a time. We found that MEC operates as an OR function when one of the sensors is performing poorly (low detection probability), while it operates as an AND function when all sensors are operating properly.

Of the individual sensors, the EEG signal showed the best performance and the BP signal showed the worst. However, adding more poor sensors does not degrade the performance of the fusion system, (i.e., the poor BP signal adds marginally to the global results). The tradeoff between the number of sensors required and acceptable system performance is a function of the particular application.

V. CONCLUSION

A two-compartment data fusion system applicable to physiological monitoring was designed and tested with human data obtained from human centrifuge experiments. Experimental results showed significant reduction of false alarm rates when using the data fusion system compared to using the results of individual sensors. This data fusion system has the ability to evaluate non-stationary and transitory biological signal patterns. A simple unifying operation rule combined with a conventional fixed fusion rule is necessary to reliably apply data fusion to physiological systems.

ACKNOWLEDGMENT

This project was supported in part by U.S. Navy, contract no. N62269-96-C-0081.

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