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Development of a Remote Vital Signs Sensor*

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Abstract

This paper describes the work at Sandia National Laboratories to develop sensors that remotely detect unique life-form characteristics, such as breathing patterns or heartbeat patterns. This paper will address the Technical Support Working Group's (TSWG) objective: to develop a remote vital signs detector which can be used to assess someone's malevolent intent. The basic concept of operations for the projects, system development issues, and the preliminary results for a radar device currently in-house and the implications for implementation are described. A survey that identified the in-house technology currently being evaluated is reviewed, as well as ideas for other potential technologies to explore. A radar unit for breathing and heartbeat detection is being tested, and the applicability of infrared technology is being explored. The desire for rapid prototyping is driving the need for off-the-shelf technology. As a conclusion, current status and future directions of the effort are reviewed.

Introduction

A sensor that can detect unique life-form characteristics, such as breathing or heartbeats, has far reaching applications in broad areas such as search and rescue, health monitoring, battlefield medicine, and security. Within the security field, a human presence sensor with the ability to assess vital signs may be useful in various types of applications, such as intrusion detection systems, vehicle portals, and personnel verification and/or monitoring. However, due to the technical challenges involved in developing such a sensor—to include the signal processing—and the inherent limitations that come with any particular technology, a specific potential application is necessary in order to constrain the problem.

This paper addresses the detection of human vital signs in order to remotely monitor personnel for a kind of anxiety that is indicative of malevolent intent (TSWG requirement).

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Research Approach

Three basic technical challenges are evident in developing a remote vital signs (RVS) sensor for personnel monitoring:

- Determining which vital signs accurately reflect anxiety
- Developing a sensor which remotely detects the vital signs
- Developing the signal processing algorithms

The multidiscipline nature of the problem requires various experts, especially within the fields of psychology and physiology. The first two challenges are currently being investigated while the signal processing cannot be addressed until a particular technology is selected. We are in the first phase of the project, which is to establish the feasibility of identifying or developing a sensor and outlining specific objectives for the project. We envision these challenges being met in gradual levels of difficulty based on increasing complex applications. For the short term, the application goal is to establish the presence of a single human within a controlled environment (room, vault) by assessing the presence of human vital signs. Two intermediate-term application goals are envisioned: (1) establish the anxiety of a human within a controlled environment, and (2) establish the presence of a human in an uncontrolled environment. The long-term goal, as mentioned in the introduction, is to establish the anxiety of a human in a non-controlled environment, such as a crowd of people, in order to determine if a person has malevolent intent.

Psychophysiological Results

We are researching the fields of polygraph and biofeedback to determine which vital signs to measure. Both fields address psychological and physiological issues, such as what vital signs can be used to assess psychological state, and how the signals are measured and analyzed. From this research, issues concerning reliability and validity of vital signs in establishing a person's psychological state become apparent. For example:

(1) Do different psychological states produce the same measurements in the physiological signals monitored?

(2) Does the same type of psychological states yield the same type of response in different people?
(3) Does the same person yield the same type of response for the same psychological state at different times?

In the field of polygraph, these issues have been studied extensively because the repercussions of the analysis of polygraph results are used in critical areas, such as criminal cases, hiring decisions, and security clearance screenings.

In essence, polygraph operators try to detect deception by assessing the anxiety caused by a person's fear of being caught in a lie. In *Truth and Deception, the Polygraph ("Lie-Detector") Technique* Reid (1982) states:

> In endeavoring to conceal the truth, have we not on occasions felt a thudding increase of the heart beat, the rush of blood to the face, an uncontrollable impulse to swallow, or other such phenomena resulting from fear over the possibility that the lie will be detected? [1]

By appealing to an individual's personal experience, Reid describes the physiological response experienced by someone lying and attributes the response to fear. Reid describes a subject who felt so sure he was going to be caught by the test that he was no longer fearful, and the polygraph assessment did not detect the subject's deception to the questions. [1]

Though not a premise in Reid's book, one could think of a polygraph exam as a physiological assessment that examines minute changes in fear or anxiety, which, for our application, may be indicative of malevolent intent. Thus, the techniques associated with assessing anxiety for polygraph are appropriate for our application. Furthermore, polygraph performance could serve as a benchmark for our application.

In order to assess one's anxiety during a lie, a polygraph evaluation relies on many factors: a specific questioning technique, an instrument to measure and display physiological signals, and the operator's analysis.

Various questioning and assessment methods are used in polygraph analysis. Two general camps exist in polygraph research: Reid (cited above) and Backster. [2] The Backster method compares relevant and control questions and assigns a response score. Based on the sum of these scores, an overall assessment of the respondents psychological state is made: "Was he/she lying?" The Reid method makes an overall assessment that is conducted by the examiner (not a score) which includes assessing information about a subject's behavior before and during a session. A major drawback to this approach is that this session can be considered an interrogation rather than a valid psychological evaluation. [2] Anecdotes abound of polygraph interrogations that have led to confessions; in fact, many complaints can be found in the literature that indicate that any black box with the mythology of the polygraph would work just as well. [2] That is, the confessions are more of a result of the interrogation, rather than the validity of the assessment.

Ample research exists, however, to support the validity of polygraph assessments. The studies vary from the type of questioning technique used, the particular physiological processes assessed, and whether the studies were done in a laboratory or in the field (criminal cases). A study published in 1992 summarizes many past results and documents results using real-life criminal guilty knowledge tests (a particular questioning method used in many laboratory experiments and considered to be the most valid questioning technique by Elaad, et. al) [3], respiration line length, and skin resistance response (physiological processes assessed). In general terms, the article shows that innocent subjects are correctly identified with a probability of 0.97 and guilty subjects are identified with a probability of 0.53. Note that since there are typically fewer guilty subjects tested than innocent subjects tested, these values represent better performance than flipping a coin. There have been studies which have better results with guilty subjects identified at a probability of 0.87 to 0.99. [2] Since our application is much less constrained than a polygraph, we could not expect to exceed these levels of performance, and should anticipate significantly lower performance.

One important constraint is the use of control questions. In order to assess deception, there is a heavy reliance on control questions during a test to serve as a baseline and for comparisons. Requiring a baseline to form comparisons is a technique also used by biofeedback researchers. One establishes a measurement for a particular person at a particular time. By using a baseline, one tries to avoid the pitfalls described by issues 2 and 3 above. However, establishing a valid baseline is not a trivial matter. Within the polygraph field, this receives much attention in the context of the questioning technique. For our application, it is solely important to note that physiological signals for a particular psychological state can vary from person to person and also over time for the same person. Analysis of a psychological state, such as deception, or in broader terms, anxiety, requires baseline signals and a trained operator for analysis--an important factor to consider for the concept of operation of the TSWG requirement.

The analysis is not only dependent on the questioning technique, but also dependent on the physiological signals measured. In the case of polygraph, blood pressure-pulse (heartbeat), respiration, and skin conductance are the signals typically used. Figure 1 shows polygraph traces for respiration and blood pressure-pulse with fine detail.

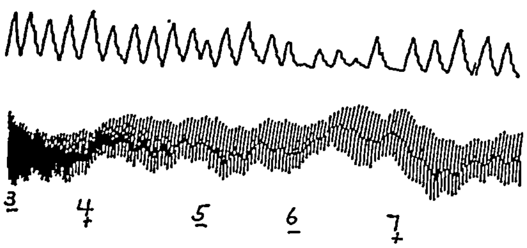

Figure 1: Polygraph Traces (Respiration and Blood Pressure-Pulse) Without Deception [1]

The top trace is respiration. Reid believes respiration is the best indicator of deception [1] while other sources argue that skin conductance is best [2]. Figure 2 includes skin conductance, which is overlaid on the blood pressure pulse.

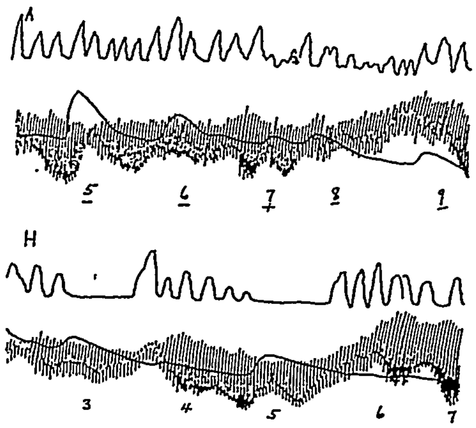

Figure 2: Polygraph Traces (with Skin Conductance) Indicating Deception [1]

The numbers indicate when a particular question is being asked, and in Figure 1 questions 3 and 5 are related to the subject of concern (5 is also a control or baseline question), and 4 and 7 are irrelevant. For Figure 2, question 6 is the control question and the others are relevant. The traces in Figure 1 are evaluated as truthful, while those for Figure 2 are evaluated as deceptive.

The respiration and blood pressure-pulse traces in the top of Figure 2 indicate deception, but the skin response does not. Skin response indicates deception, but the other traces did not for the bottom traces of Figure 2. Without getting into the details of the analysis, the point to note is the complexity of the signals and how the use of control and irrelevant questions requires a trained operator to make an assessment of the physiological signals measured. Thus, the concept of operations for the TSWG application would involve having a trained operator to analyze the physiological signals to make an assessment.

There are other physiological processes which can be used to assess one's psychological state. The polygraph field has considered the following processes:

Pupil diameter	Electrical changes in muscles
Skin potential	Body temperature
Cerebral blood flow	Finger pulse volume
Skin blood flow	Brain waves
Instantaneous pulse rate	

However, these are not in prevalent use, and, consequently, not as extensively documented as the processes depicted in the traces shown.

In the biofeedback field, where the objective is to promote the acquisition and self-control of psychophysiological processes by using equipment to. teach someone to manipulate what would normally be considered involuntary events in order to promote better health, many processes have already been explored. However, skeletal muscle tension, peripheral vasoconstriction (peripheral blood vessel diameter), and skin conductance tend to be singled out as commonly associated with overarousal, that is, states of anger, fear, excitement, and/or arousal. [4] (Note that the same processes are used for different psychological states.) Skeletal muscle tension is inferred from an electromyography (EMG) which measures the electrical correlation of muscle contraction. Peripheral vasoconstriction is inferred by measuring the skin temperature of a finger or by using a photoplethysmograph, which measures the translucence of the finger. Skin conductance is measured in the same manner as the polygraph. More details can be found in References 4 and 5. We are currently in the process of expanding our research to the general field of anxiety to see if any other physiological processes for our application can be identified. However, based on the processes identified by the polygraph and biofeedback fields, one can start evaluating potential technology which may be useful in remotely measuring these more informative physiological processes:

- respiration
- blood pressure-pulse
- skeletal muscle tension
- peripheral vasoconstriction
- skin conductance

Technology Evaluation

A survey of potential technology for detecting the presence of a human by some life-form characteristic other than motion, beam blockage, capacitance change, and/or infrared presence was conducted by Sandia in 1995. Several promising technologies were identified from the dozens of technologies evaluated. Of those identified, which included surface acoustic wave, vibration detectors, laser radar, light detection and ranging, passive millimeter wave, and tiltmeter weighing devices, the micropower impulse radar (MIR) was singled out as the most promising.

Since the 1995 study, other systems have been identified with the potential to detect respiration and breathing. The Hughes Advanced Electromagnetic Technologies Center has developed radar and ultrasonic technology. Although not specifically designed to detect heartbeats and respiration, these technologies have the potential to do so, but in very constrained situations. In essence, the motion detection technology is capable of detecting very minute changes in movement. Should a subject be very still, the minute changes of breathing and heartbeats can still be detected. The Georgia Tech Research Institute Sensors and Electromagnetic Applications Laboratory has developed a radar that has demonstrated the capability of measuring heartbeats and respiration, however, under the constraint of having the subject standing still.

We have not established any technology to remotely measure skeletal muscle tension or skin conductance. We are currently exploring the potential of infrared imaging technology for measuring skin temperature in order to infer peripheral vasoconstriction. Because of the demonstrated potential of radar technology, we performed in-house studies using the MIR sensor to develop a better understanding of some of the issues.

Micropower Impulse Radar Technology

MIR technology was developed at Lawrence Livermore National Laboratory and is based on a novel form of radar known as ultra-wideband impulse radar. A very short electromagnetic pulse is propagated from the sensor and only the echoes that reflect from a defined range are detected. Two models are currently being evaluated at Sandia. The first model, a motion sensor, is a standard MIR board that has been modified to have a maximum range of approximately 17 feet, but is currently set at a range of approximately 10 feet. The motion sensor is being evaluated to determine if it has the capability to remotely detect heartbeats and/or respiration from a distance. The second model, an organ motion sensor, has been modified to have a range of approximately 2 feet, and is intended to be placed against the chest for heartbeat monitoring.

The output signal of the MIR devices were sampled using LabVIEW® (data acquisition software from National Instruments) at a sampling rate of 200 Hz. Although heartbeat and respiration frequencies are located at very low levels (< 2 Hz), this sampling rate prevented aliasing. Heartbeat measurements were taken from the subjects by placing the organ motion sensor directly over the heart for 20 seconds. The subject was required to hold his breath while the data was collected in order to provide a clear heartbeat trace for validation purposes. The benchmark for validation was established by a nurse who measured the subject's pulse during the tests. For Figure 3, the rate measured by the nurse was 76 beats per minute (bpm) which is approximately 1.3 Hz. This rate will be compared to the rate obtained from the data through spectral analysis techniques discussed below.

Note that the traces in Figure 3 do not resemble those of an electrocardiogram (ECG), nor the blood-pressure pulse shown in Figures 1 and 2. The MIR devices are merely measuring the motion of the heart, and the output of the MIR does not correlate directly with a change in distance due to internal processing. Each normal heartbeat is the result of an electrical stimulus and a mechanical response. When the cardiac muscle cells are strong and able to respond to the electrical stimulation, depolarization and repolarization are coupled with the mechanical responses of contraction (systole) and relaxation (diastole). At this time, however, we do not know whether the MIR signals are penetrating the body and measuring the mechanical responses of the anterior part of the heart, or is measuring the chest movement caused by these mechanical responses.

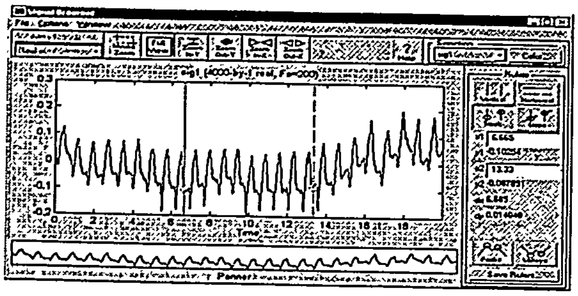

Figure 3: Heartbeat Trace of Test Subject

The other physiological process, respiration, was measured using the MIR motion sensor. The motion sensor was placed approximately 2 feet away from the test subject's chest and measurements were taken for 60 seconds. The subject's movements were very limited except for the occasional chest contractions. The respiration trace of Figure 4 is somewhat similar to the heart trace of Figure 3, but since there is greater movement of the chest with respiration, the amplitude and duration are more pronounced. As with the heart rate measurements, a nurse was used to establish a benchmark by measuring the subjects respiration rate. For this particular subject, the rate measured by the nurse was 12 respirations per minute (rpm) which is 0.20 Hz. This rate will be compared to the rate obtained from the data through spectral analysis techniques described next.

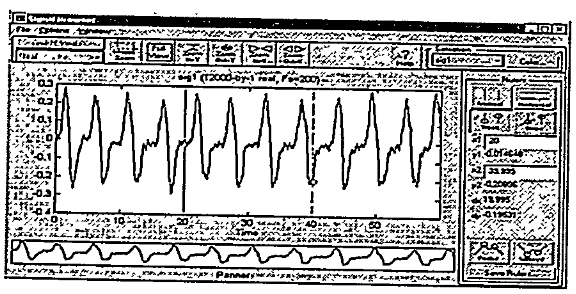

Figure 4: Respiration Trace of Test Subject

Using the MATLAB® Signal Processing Toolbox, both the heartbeat and respiration data were filtered (in order to remove noise) before performing spectral analysis. For the heartbeat data, a finite impulse response (FIR) filter was used with a pass band of 0.5 to 2 Hz (30 bpm to 120 bpm) which will pass heartbeats within the normal resting heart rate range for an adult of 60 to 100. [6] The pass band for the respiration data was set at 0 to 0.6 Hz (0 rpm to ~30 rpm). The filtered signals were then analyzed using the multitaper method for spectral analysis (see Reference 7). Figure 5 shows a "zoomed-in" view of the heartbeat spectrum with a time-bandwidth product of 4 and a 2048 point fast Fourier transform (FFT).

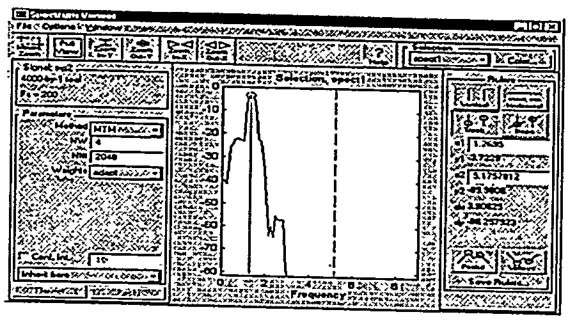

Figure 5: Spectral Display From Filtered Heartbeat Trace of Subject

As shown in the figure, there is only one main peak above the 20 dB region. This peak corresponds to a frequency of 1.27 Hz or 76.2 bpm which compares well with the 76 bpm benchmark measured by the nurse. Figure 6 shows a zoomed-in view of the respiration spectrum with a time-bandwidth product of 4 and a 4096 point FFT. The peak above 0 dB corresponds to a frequency of 0.196 Hz or 11.8 rpm which also compares well to the 12 rpm benchmark measured by the nurse.

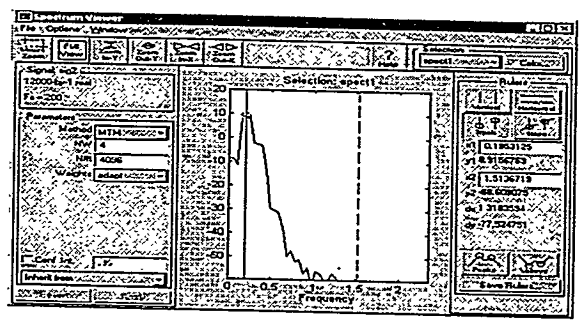

Figure 6: Spectral Display From Filtered Respiration Trace of Subject

Although these processing techniques have been able to extract heart and respiration rates from the test subjects under the highly controlled test situation (i.e., restricted movement), more research will be required before these physiological processes can be measured from a moving subject. To demonstrate the motion artifacts, a test was performed with the subject sitting 2 feet from the MIR motion sensor, but moving his head, arms, and fingers during the measurement phase. Figure 7 shows the motion sensor output of the 60-second measurement period.