

MONITORING OF PERIORBITAL BLOOD FLOW RATE THROUGH THERMAL IMAGE ANALYSIS AND ITS APPLICATION TO POLYGRAPH TESTING

I. Pavlidis¹, J. Levine²

¹Honeywell Laboratories, Minneapolis, MN, USA

²Mayo Clinic, Rochester, MN, USA

Abstract- In the present paper we describe a novel method for scoring polygraph tests using thermal image analysis. Our method features three stages: image acquisition, physiological correlation, and pattern classification. First, we acquire facial thermal imagery using an accurate mid-infrared camera. Then, we transform the raw thermal data to blood flow rate data through thermodynamic modeling. Finally, we classify the subject as deceptive or non-deceptive based on the nearest-neighbor classification method. We perform our analysis on the periorbital area of the subjects' faces. Our previous research [1][2] has indicated that the periorbital area is the facial area affected the most from blood flow redistribution during anxious states.

We present promising experimental results from 18 subjects. We henceforth anticipate that thermal image analysis will play an increasingly important role in polygraph testing as an additional scoring channel. Our ultimate objective is to increase the accuracy and reliability of polygraph testing through the fusion of traditional invasive 1D physiological measurements with novel non-invasive 2D physiological measurements.

Keywords - Thermal imaging, polygraph testing, mid-infrared, far-infrared, thermodynamic modeling, blood flow rate, nearest neighbor classification.

I. INTRODUCTION

Polygraph testing is a standard security procedure favored by the U.S. government. The objective of the polygraph testing is to ascertain if the subject under investigation truthfully or deceitfully answers the questions at hand. Specially trained psychologists structure the questions to maximize elicitation. During the testing three physiological parameters are closely monitored: blood flow rate, breathing rate, and perspiration rate. They are all recorded using invasive methods and produce scalar values over time (signals). Then, a scoring system is used to quantify the subject's response and classify it as deceitful or truthful.

The success rate for realistic polygraph testing varies but on average is in the neighborhood of 90%. When the test is administered experimentally on the basis of a mock crime scenario, the success rate is even lower. The U.S. government is interested in increasing this rate through the use of additional information channels [3]. One very promising channel is the use of infrared facial image analysis. There are several advantages to this method:

- 1) It is non-invasive. This is very important in the context of polygraph testing where it is important for the subject to feel as comfortable as possible.

- 2) After appropriate processing the thermal imagery can yield the same type of physiological information as one of the traditional polygraph channels - i.e. blood flow rate. The major difference is that this information is now 2D and not 1D across the timeline. This is at least an order of magnitude more information than the traditional channel can generate.

- 3) The raw thermal data provide a completely retraceable record. That means that if a new or more improved method of extracting physiological information is devised in the future, then the stored thermal data can be re-processed and the corresponding legacy test re-scored without the need to be physically repeated.

In the rest of the paper we describe our experimental design (Section II), the image acquisition set-up (Section III), the method we follow to convert raw thermal data to blood flow rate data (Section IV), the pattern recognition method we use to classify blood flow rate patterns (Section V), and an analysis of our experimental results (Section VI). Finally, we conclude at Section VII.

II. EXPERIMENTAL DESIGN

The polygraph tests were designed around a mock crime scenario. The crime scene involved the stabbing of a woman with a screwdriver. Some of the subjects were programmed 'innocent' and some were programmed 'guilty'. The guilty subjects enacted the crime as if it were real. A mannequin played the role of the stabbed woman in the crime scene. The theft of a \$20 bill has been identified as the motive for the crime. The innocent subjects did not have any knowledge or association with the crime scene. Psychologists in the Department of Defense National Polygraph Institute (DoDNPI) structured the type and sequence of questions.

One of the most important questions for the determination of guilt or innocence was Question 10 (Q10), which in our case was phrased: "Do you have that stolen \$20 on you right now?" For Question 10 (Q10) alongside with the traditional invasive measurements we recorded digital clips of thermal video data for each subject. Our recording started right before the examiner expressing the question until right after the subject was giving his/her answer. The average recording length per subject was 300 frames at 30 frames/sec.

III. IMAGE ACQUISITION SET-UP

We have used a cooled mid-infrared camera, the Radiance HS by Raytheon. The Focal Plane Area (FPA) of the camera is sensitive to the 3-5 μm waveband and its size is 256x256 pixels.

We have anticipated that temperature sensitivity will be very important in our experiments since we expected only subtle stimuli within the mock crime context and consequently infinitesimal facial temperature changes. The thermal sensitivity of Raytheon Radiance HS is $\text{NETD}=0.025^\circ\text{C}$.

To ensure the highest level of temperature reading accuracy we have calibrated the Raytheon Radiance HS camera using an external black body. Specifically, we used the 2008 Model by Santa Barbara Infrared with thermal

sensitivity equivalent to that of our camera (NEDT=0.025°C). We set the minimum and maximum calibration temperatures to $T_{\min}=29^{\circ}\text{C}$ and $T_{\max}=38^{\circ}\text{C}$ respectively. Based on our experimental experience these are the temperature extremities one can find across the human face.

Since we operated in the mid-infrared spectrum, to eliminate any effect on the measurements from illumination we performed the experiments in a dimly lit room. The thermal camera was connected and controlled by a PC that ran special software. Every video clip per question and subject was recorded directly on the hard disk.

IV. THERMODYNAMIC MODELING

A. Previous Work

In [1] [2] we described a method for detecting anxiety through thermal facial image analysis. We reproduced anxiety feelings by applying a startle stimulus to subjects. Specifically, we allowed subjects to relax for about 10 minutes in a dimly lit room. Then, without prior notice we were producing an instantaneous loud noise (60 dB) and we were recording via a far-infrared camera (ExplorIR by Raytheon) the face of the subject from just before to just after the startle event. The results of thermal image analysis demonstrated that fright is accompanied by significant warming in the periorbital area (see Figure 1). This warming was attributable to increased blood circulation in the area around the eyes. The whole pattern makes physiological and evolutionary sense since it represents (a hitherto unidentified) mechanism to facilitate rapid eye movements during preparedness for flight.

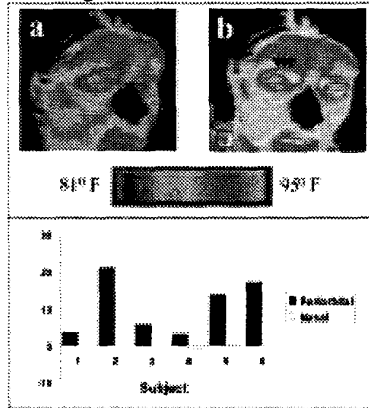
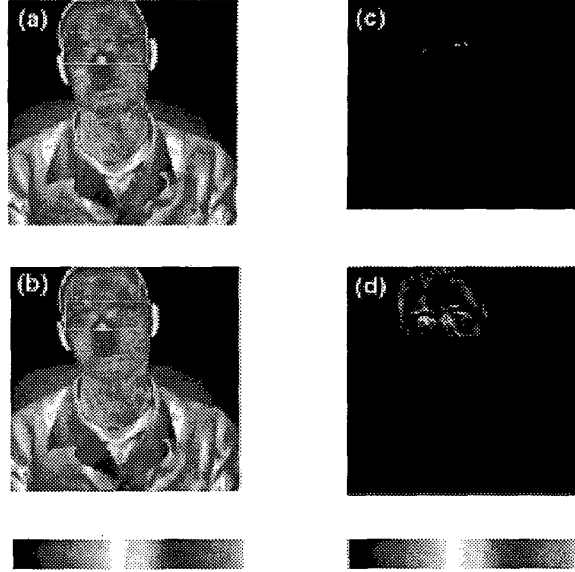


Figure 1: Thermal images of the face for a subject (a) before and (b) 300 msec after an instantaneous startle. Arrows indicate local warming in the periorbital area. The color bar depicts the false coloring scheme from the lowest (81°F) to the highest (95°F) temperature. (c) Changes of the average pixel value in the periorbital and nasal areas with auditory startle. The changes are depicted for each subject ($n=6$ subjects). Positive deviation represents local warming and negative deviation, cooling.

B. From Raw Thermal Data to Blood Flow Rate Data

In the polygraph test setting one could visually observe that the temperature changes around the eyes and in the face in general were very subtle, almost unnoticeable (see Figure 2). This was in stark contrast to the very noticeable temperature changes in the case of the startle experiments (see Figure 1).

We argue that this disparity is due to the comparatively subtle stress imposed on the polygraph subjects in the context of the mock crime scenario. Therefore, our goal was to find a method that will amplify the weak pattern buried in the raw thermal data.



2 (a) Raw thermal snapshot of subject 3 answering question 10 (towards the beginning). (b) Raw thermal snapshot of subject 3 answering question 10 (towards the end). The difference between the two left images is imperceptible. The rectangles delineate the periorbital and forehead areas under monitoring. (c) Visualization of the blood flow rate in subject's 3 face as he answers question 10 (towards the beginning). (d) Visualization of the blood flow rate in subject's 3 face as he answers question 10 (towards the end). The difference between the two right images is significant. The colorbars index the range of the temperature and blood flow rate intensities from the lowest to the highest value.

The fluctuation of temperature in the various facial areas is primarily due to the changing blood flow rate. Thermodynamic modeling shows that the blood flow rate is inversely proportional to the square of the skin temperature deviation from the temperature at the core of the human body. This non-linear relation amplifies the weak temperature change patterns observed in polygraphy subjects and brings the information noise down to the levels of the startle stimulus experiments (see Figure 2).

By following similar development to the one reported in [4] and after assuming that the metabolic heat factor is negligible, we obtain the following thermodynamic equation:

$$\frac{dV_s}{dt} = \frac{T_B(C_s + K_c/(3d)) - C}{(T_B - T_s)^2} \frac{dT_s}{dt}$$

where,

V_s is the blood flow rate at the skin level,

$T_B = 310^{\circ}\text{K}$ is the blood temperature at the body core,

T_s is the skin temperature,

$K_c = 0.168\text{kcal}/\text{m}/\text{h}/\text{K}$ is the thermal conductivity of skin,

d is the depth of core temperature point from skin surface, C is a constant.

For calibrated thermal imagery, we can calculate the discrete-time approximation to the derivative of the temperature dT_s/dT as the difference between a pair of images normalized by the number of sample frames between the respective acquisition times. The expression $T_B(C_s + K_c/(3d)) - C$ represents a constant. Therefore, we can estimate the term dV_s/dT except for an unknown scale factor. The expression for dV_s/dT can be integrated numerically to obtain an estimate for V_s . To arrive at Equation (1) we have considered the metabolic heat component as negligible.

By solving Equation Error! Reference source not found. for every point in the image we transform the raw thermal data to blood flow rate data. To ensure a meaningful application of Equation Error! Reference source not found. we crop the image so that it contains only the subject's face and no background. We perform the cropping at the first frame of each video clip and the cropping dimensions apply across the timeline till the end of the particular question-answer session. This assumes a stationary subject for the short duration (5-10 sec) of the question-answer session. Based on our experimental experience the 'stationary subject' assumption is realistic. Occasionally, however, some of the more agitated subjects move noticeably even within short time periods. In these cases the thermodynamic Equation (1) is applied on the wrong points across the timeline and its solution should not be considered reliable.

Also, we provide the opportunity to the user to delineate the periorbital and forehead areas for each subject in each question (see Figure 2 (a) and (b)). The delineation takes place on the first frame of the video clip and is also based on the 'stationary subject' assumption. Within the delineated periorbital and forehead areas we compute the respective average blood flow rates for each frame. This produces two signals across the question timeline: one 'eye' and one 'forehead' signal. We use these signals as input to our pattern recognition algorithm for subject classification to the deceptive or non-deceptive category.

V. PATTERN CLASSIFICATION

We have found through visual observation that only the 'eye' signals carry significant discriminating power. This observation was consistent with our previous laboratory findings [1] [2] about the importance of periorbital blood flow rate in anxious states. Therefore, we use the 'eye' signals as feature vectors in a nearest neighbor (NN) classifier [5] setting. We opted for such a simple classifier based on the characteristics of the problem at hand. In particular:

1) This is a high dimensionality problem. The 'eye' signal, which serves as the feature vector has 300 values (one for each frame in the question). Also, no prior probabilities were given to us regarding the deceptive and non-deceptive

population. Therefore, the application of a Bayesian classifier is not feasible.

2) The current set of subjects we have at our disposal is still relatively small. Therefore, neural network approaches that require significant sample sets for training cannot be reliably applied.

By nearest in NN we mean the smallest Euclidean distance in 300-dimensional space, where 300 is the number of frames in the Question 10 (Q10). Our aim is to classify the majority of the subjects (test subjects) based on their distance from a small number of control subjects (4 subjects in our case). The population of control subjects should be unbiased.

Alternatively, we can establish ideal 'eye' signals for the deceptive and non-deceptive case and measure the respective Euclidean distances. These ideal deceptive and non-deceptive 'eye' signals should correspond to the expected physiological response in stressful and non-stressful situations. Picking ideal (control) 'eye' signals from our subject population is a mere convenience and assumes that the selected 'eye' signals are clear cut cases that would always be classified correctly by our method.

VI. EXPERIMENTAL RESULTS

We have examined a set of 32 polygraphy subjects. Data from only 22 of those were deemed of legitimate use. We have lost data from 10 subjects due to sizeable human and machine errors ('contamination'). From the 22 admissible subjects we have excluded 4 more subjects because their examination took place immediately after lunch. For those 4 subjects we anticipate the existence of a significant metabolic heat component, something that our current model cannot handle.

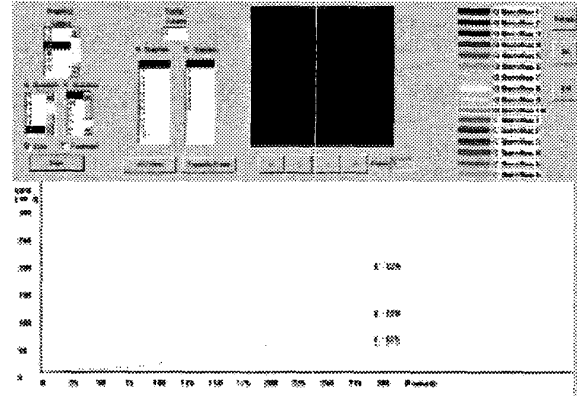


Figure 3: 'Eye' signals for control subjects S18(ND), S20(D), S25(ND), and S29(D). The signals correspond to the average blood flow rate these subjects exhibited for question 10 (Q10) across the timeline (300 frames). It is clear from the diagram the trend of deceptive subjects to cluster at the top and of non-deceptive subjects to gravitate towards the bottom. The 'eye' curves start from zero because we assume zero initial conditions for the solution of the differential Equation (1). The figure also shows part of the graphical user interface that was specially designed to accommodate experimentation.

We were provided with ground-truth information for 4 clear-cut subject cases- two deceptive (S20 and S29) and two non-deceptive (S15 and S25). One can observe in Figure 3 how the 'eye' signals for the four controlled subjects are shaping across the timeline. This is a rather consistent behavior and

matches our physiological hypothesis. 'Eye' signals from the deceptive control subjects have a rather steep ascend, while 'eye' signals from the non-deceptive control subjects have a more moderate ascend. Therefore, these signals would have always been classified correctly by our method and can be considered as ideal (control) 'eye' signals.

TABLE shows the classification results for the thermal image analysis system. The classification cells featuring a color background denote misclassification in part of the thermal image analysis system. Based on the results of TABLE, the current correct classification rate for the thermal image analysis method is CCR= 78%, the false alarm rate is FAR=5%, and the missed detection rate is MDR=17%. These initial results clearly indicate that the method can afford significant discriminating power.

TABLE I

EXPERIMENTAL RESULTS FOR THE NN CLASSIFICATION METHOD.

Subject Classification	
3	D
5	ND
6	D
8	ND
9	ND
10	ND
12	ND
13	D
14	ND
15	ND
17	ND
18	ND
19	D
20	D
21	ND
23	ND
25	ND
29	D

Color Code	Correct Classification
	False Alarm
	Missed Detection

VII. CONCLUSION

We have invented, developed, and tested a very promising thermal image analysis method for polygraph testing. Currently, the method achieves up to 78% correct classification rates in very difficult mock crime scenario testing. This performance is in par with the performance of the well-established and thoroughly researched traditional scoring methods based on invasive measurements.

Our method, once refined, can serve as an additional channel for increasing the reliability and accuracy of traditional polygraph testing.

In our immediate future plans we contemplate the following steps for drastically improving our initial thermal polygraphy method:

1) Investigate alternative features and classification schemes to further improve the performance of the system.

2) Develop an algorithm that will track the human head as it moves around during the length of the polygraph testing. This is of fundamental importance for the accurate solution of the differential thermodynamic equation that operates point-wise and across frames. Currently, we solve this equation assuming a completely stationary subject for short periods of time. This is a practical but not extremely accurate assumption. Some of the most agitated subjects move noticeably through each question and answer session. In these cases the thermodynamic Equation (1) is applied at the wrong points in portions of the timeline, which may compromise the validity of the entire computation.

3) Assuming that we have the face tracker in place, we can develop a network of fiducial points where we will monitor the blood flow rate across the face over time. In this manner we will start making true use of the 2D nature of our information. Please note that we currently compute the average blood flow rate in the periorbital area and in essence we fall back to 1D (signal) information. Averaging the blood flow rate over a substantial facial area is more tolerant to registration errors and is the only practical alternative in the absence of a facial tracker.

4) Perform further experiments to increase our training and testing base. This will allow the application of more sophisticated classifiers.

ACKNOWLEDGEMENTS

Our research was supported by grant #DABT60-00-1-1003. We would like to thank Dr. Andrew Ryan, Chief of Research at the DoD Polygraph Institute for his generous support. We would also like to acknowledge the valuable help of Dr. Dean Pollina, Research Psychologist at the DoD Polygraph Institute.

REFERENCES

- [1] I. Pavlidis, J. Levine, and P. Baukol, "Thermal Imaging for Anxiety Detection," *2000 IEEE Workshop on Computer Vision Beyond the Visible Spectrum: Methods and Applications*, pp. 104-109, Hilton Head Island, South Carolina, June 16, 2000.
- [2] J. Levine, I. Pavlidis, and M. Cooper, "Remote Detection of Fearfulness Using Thermal Imaging of the Face," to appear, *The Lancet*.
- [3] C. Holden, "Panel Seeks Truth in Lie Detector Debate," *Science*, vol. 291, no. 9, p. 967, 2001.
- [4] I. Fujimasa, T. Chinzei, and I. Saito, "Converting Far-Infrared Image Information to Other Physiological Data," *IEEE Engineering in Medicine and Biology*, Vol. 19, No. 3, pp. 71-75, 2000.
- [5] E. Gose, R. Johnsonbaugh, and S. Jost, *Pattern Recognition and Image Analysis*, Prentice Hall, Upper Saddle River, NJ, 1996.