

# 使用紅外線熱電感測器實現人員即時辨識之生物檢測系統

研究生：方建舜

指導教授：許根玉

國立交通大學 電機學院

光電工程研究所

## 摘要

在本研究中我們提出新穎的光學運算感測系統，在系統中引入生物測定觀念以及非成像式之光學特徵擷取技術來捕捉步行者之動態熱像特徵，加上智慧型特徵分類訓練法則，成功地實現了人員即時辨識。

生物體特徵的選取是生物檢測/辨識系統中最關鍵的一環。從熱源的觀點來看，人體是一個非常好的紅外線輻射源，在常溫環境中人體會持續地散發出紅外輻射。而熱源的分佈強度取決於體型的高矮胖瘦及皮膚上各處的紅外輻射發射率。當人在行走時，因為身體各個部位的擺動方式不同，產生了不同風格的動態行走特徵，因此，結合了身材特徵以及個人的行走風格，即使走在同一路線上，所散發出的紅外熱源分佈對於周圍的感測器也會產生獨特的訊號。

在生物特徵擷取方面，我們使用紅外線熱電感測器，此元件在室溫下對於偵測紅外輻射訊號有很好的工作效能，且有低功率損耗、低成本的優點，因此被廣泛的應用在各種不同的系統中。當感測器感應到溫度變化時，感測器內晶體的熱電特性，將會產成電荷充電效應，進而轉換產生電壓訊號。我們利用感測器去偵測人員走動所產生的熱輻射，系統中以吾人發明的特殊菲涅耳透鏡陣列，結合光學運算及感測技術，達到無需成像直接捕捉步行者之熱像生物特徵的效能。

在特徵分類辨識方面，本論文發展出兩套分別以類比式生物特徵以及數位式生物特徵為基礎的生物檢測/辨識系統。我們成功的展示藉由適當的感測模組結構，加上特徵擷取方法以及特徵訓練演算法，這些生物檢測系統可以達成固定行走路線及自由路線的即時人員辨識並有非常好的辨識效果。

# Pyroelectric Infrared Biometric Systems for Real-Time Human Identification

Student: Jian-Shuen Fang

Advisor: Ken Y. Hsu

Institute of Electro-Optical Engineering  
College of Electrical and Computer Engineering  
National Chiao Tung University

## ABSTRACT

In this study, we proposed novel designs for computational systems that use biometrics and non-conventional imaging approaches to capture thermal motion features of humans to achieve real-time path-dependent and path-independent gait for human identification.

Feature representation is key to biometric recognition system. From a thermal perspective, each person represents a distributed infrared source, the distribution function of which is determined by shape and IR emissivity of the skin at every point. When humans walk, the motion of various parts of the body, including the torso, arms, and legs, produces a characteristic signature. Combined with idiosyncrasies of carriage, heat will uniquely impact a surrounding sensor field, even while the subject follows a prescribed path.

The pyroelectric infrared (PIR) sensor is a high performance IR radiation detector and its low cost and low power consumption make it attractive for a wide range of applications. When the temperature changes, electric charge will built up on the sensing element by virtue of pyroelectricity. The resulting charge translated into a current that a current-to-voltage transductance amplifier converted to a voltage signal. By measuring the sensor response generated by a person walking within the field of view of a PIR sensor module, we can model

this response data to a code vector that uniquely identifies the person.

We have developed two PIR feature-generating sensor systems. One system is analog, the other digital, and both are derived from the signals generated by humans crossing the detection areas. We successfully demonstrate that by selecting suitable sensor configurations and feature extraction/training algorithms, the sensor systems are capable of performing human identification.



# 誌謝

## (Acknowledgements)

首先我要以最誠摯的敬意感謝我的指導老師 許根玉教授，承蒙老師以其豐富的學識與經驗指引我研究的方向，從題目的確立、觀念之釐清以至論文口試的完成，均蒙師不厭其煩地予以教導與指正。而老師本身治學的精神與謙虛、寬容的待人處事態度更是學生的典範，也是學生自許的目標。在學期間受老師提攜，使學生有很多機會參與國內外學術研討會，拓展了學生的視野。僅此向恩師致上最真誠的謝意與敬意，老師為學生的一切，學生銘記在心。

本論文得以順利完成要特別感謝杜克大學(Duke University)光電中心/電機與電腦工程學系的David J. Brady教授與Bob D. Guenther教授謝謝您們在我赴美一年這段期間提供我很多的資源、機會和很大的空間，讓我自由地揮灑、嘗試、歷練和學習，使的我這一年中在生醫光電這個領域中有很大的突破。最後階段您們還特地遠從美國來台灣參加我的論文口試，這份恩情學生感念在心，由衷地謝謝您們。

在本論文完稿之際，我想將這份喜悅分享給我的啟蒙恩師：元智大學電機工程學系陳祖龍教授，感謝您帶我進入光電科學這豐富的領域，在我大學及研究所時期您悉心指導與諄諄教誨，奠定了學生日後深造的基礎，我滿懷感激地想藉由這本論文來謝謝您對我的栽培。

口試期間，承蒙 祁姓教授、張明文教授、謝太炯教授、林志民教授及林烜輝教授於百忙中撥冗費心審查，並提供許多寶貴的意見與教誨，使學生論文更加完善，由衷地向老師們致上最誠摯的謝意。

在學期間，感謝蘇德欽教授、林烜輝教授、謝美莉教授、Vera Marinova教授在學業及研究方向上提供許多寶貴的建議。感謝明郎學長、義男學長、仁崇、俊華、博宇、謹綱、百合、建成、宏璋、俊誌、安澤、立偉、士芄、伯霖、晟齊、容容在研究上、生活上及未來方向上，都給我許多的支持與鼓勵。感謝同窗好友森益、鴻章、仁宇、晴如、桂珠、永松、企桓、博任、及志成的相互提攜鼓勵，一起分享在研究過程中的甘苦。感謝杜克大學的好友們白明道博士、曾秀如博士、王俊元博士、惠芝、林士傑博士、吳建德博士、宣燁、建元、Phil、Jason夫婦、Sweettea夫婦、Morris、Henry、Wendy及如親兄弟情誼般的Vivide，謝謝你們，讓我非常享受在杜克大學的時光，與你們在一起的那段時間真的很快樂。另外，也要感謝杜克大學DISP實驗室的好友們，Yunhui Zheng博士、Yanqia Wang博士、Evan Cull博士、Cristina Fernandez、Steve Feller、Mohan Shankar、Michael Gehm博士、Scott McCain博士、Andrew Portnoy、Prasant Potluri博士、John Burchett博士、Nikos Pitsianis博士，不論是在研究、學業、生常生活、或玩樂上，與你們的互動讓我學習到很多，也增廣我許多見聞。也要感謝我們光電所上美麗能幹的的助理，淑惠、怡芬、靖純、雅鈴、許姐，跑去所辦跟你們聊天是我研究之餘最佳的放鬆方式，也要特別謝謝你們對我在各方面溫暖的情誼。

在這裡我也要特別提到我的最佳拍檔，Qi Hao(郝祁)博士，與你的互動讓我成長、獲益許多，無論是在研究方法，論文寫作，理論推導，甚至在生活中觀念、人生方向，政治觀點，總是能激盪出許多火花，產生各種豐富的結果，也特別恭喜你在畢業後短時間內即受聘任教於阿拉巴馬大學(University of Alabama, USA)，相信你將來一定是一位傑出的教授，無論是在研究上還是教學上，祝福你，也感謝你。

我更要特別感謝我的父母!!您們全心全意的為家裡付出，總是把最好資源留給我們，栽培我們四個兄弟姐妹，您們是我克服各種困難最大的支柱，感謝您們多年來的犧牲與奉獻，沒有您們這樣的付出將不會有今天的我，我愛您們。感謝岳父、岳母在當時尚未完全開放的高中時期允許/支持我跟您們女兒交往，讓我有機會擁有一位體貼、賢淑的女友/老婆。感謝我的高中恩師 陳文森老師一直以來適時適切的引導，讓我在面對各種抉擇時有最佳的諮詢參考。當然我的妻子宛真，在我人生這重要的階段給我永無止盡的支持、鼓勵與照顧，你是我信心與動力的來源，擁有你是我的福氣。另外，感謝上天送給我最棒的畢業禮物：我的寶貝兒子方翊安，你的誕生帶給我莫大的喜悅。

最後僅以此論文獻給我最敬愛及思念的祖父母及曾祖父母！



## Contents

Chinese Abstract.....	I
English Abstract.....	II
Acknowledgement.....	IV
Contents.....	VI
List of Figures.....	IX
List of Tables.....	XIII

## Chapter 1. Introduction

1.1 Biometric Systems and Biometric Features.....	1
1.2 Human Infrared Sensing .....	4
1.3 Human Thermal Model.....	5
1.4 Computational Imaging System.....	6
1.5 Motivation.....	7
References for Chapter 1.....	9

## Chapter 2. Pyroelectric Infrared Sensor Module

2.1 Pyroelectric Sensors.....	14
2.1.1 Types of Pyroelectric Sensors.....	15
2.1.2 Sensor Characterization.....	15
2.2 Power Coupled to Detector.....	18
2.3 Fresnel Lens Arrays.....	20
2.4 Micro-controller and Transceiver.....	23
2.5 Sensor Platform Construction.....	23
2.5.1 The Features of the Rapid Prototyping Machine EDEN330.....	24

2.5.2	Fabrication Process.....	25
2.5.3	Fabricated Structure.....	27
	References for Chapter 2.....	29

### **Chapter 3. Real-time Path-dependent Human Identification**

3.1	Identification Process.....	30
3.1.1	Data Training Using Principal Components Regression.....	31
3.1.2	Multiple Hypothesis Testing.....	34
3.1.3	Experimental Setup.....	36
3.1.4	Analog Feature Representation.....	36
3.1.5	System Parameter Optimization and Experimental Results.....	38
3.2	Real-time System Implementation.....	45
3.2.1	Feature Training Using Maximum Likelihood Principal Components Estimation.....	48
3.2.2	Modified Multiple Hypothesis Testing.....	52
3.2.3	Experimental Results.....	53
3.2.3.1	Receiver Operating Characteristic Curve for Threshold Selection.....	58
	References for Chapter 3.....	62

### **Chapter 4. Real-time Path-dependent and Path-independent Human Identification Using Hidden Markov Model**

4.1	Introduction.....	63
4.1.1	Hidden Markov Models.....	65
4.1.2	Model Training.....	68
4.1.3	Multiple Hypothesis Testing.....	69

4.2 Digital Feature Generation.....70

4.3 Experimental Results for Path-dependent Recognition.....74

4.4 Experimental Results for Path-independent Recognition.....83

References for Chapter 4.....87

**Chapter 5. Conclusions**

5.1 Summary of Work.....89

5.2 Discussions.....92

**Vita**.....94





## List of Figures

Fig. 1.1 Black-body radiation curve of human body at 37 °C.

Fig. 1.2 A typical computational system.

Fig. 2.1 Experimental setup for sensor characterization.

Fig. 2.2 Step response of the pyroelectric sensor.

Fig. 2.3 Polar plot of visibility of dual element pyroelectric detector.

Fig. 2.4 Response of the dual element pyroelectric detector with distance.

Fig. 2.5 Beams formed by a single lens on a lens array. The two beams correspond to each of the elements in a dual element detector.

Fig. 2.6 (a) Signal obtained from a dual element pyroelectric detector with a person moving across the FOV of a single lens in front of a detector. (b) Signal obtained from the detector with a person moving in the opposite direction.

Fig. 2.7 Characteristic of FOV of Fresnel lens array. Each lens on the array creates two beams having an angular visibility of 3° separated by 1°.

Fig. 2.8 Response signal of a dual element pyroelectric detector to a person with multiplex visibilities generated by a Fresnel lens array.

Fig. 2.9 The EDEN330 Rapid Prototyping device and water jet.

Fig. 2.10 The Object PolyJet Process.

Fig. 2.11 An example completed object set.

Fig. 2.12 A finished product set.

Fig. 2.13 A sensor module for spectral feature extraction.

Fig. 2.14 An example sensor module contains 4 PIR detectors and with periodic sampling masks.

Fig. 3.1 The diagram of the proposed identification system.

Fig. 3.2 An experimental setup for human identification. The center of the sensor element is

perpendicular to the path.

Fig. 3.3 Output signals for two different individuals walking across the field of view of one sensor unit.

Fig. 3.4 The spectra for two different individuals by performing the Fourier transform of the temporal signals in Fig. 3.3.

Fig. 3.5 Four different masks for selection of lens elements.

Fig. 3.6 Each column is for different speed levels (fast, moderate, and slow, respectively). Each row is for different element numbers of Fresnel lens arrays (1, 5, and 11, respectively). Each subfigure contains 20 superimposed data sets which were gathered from 20 independent walks at the same speed. (a) The data sets of Jason. (a) The data sets of Bob.

Fig. 3.7 The supervised clustering results upon 6 labels for 120 data sets collected from the sensor unit placed at the height of 80 cm. (a) Data from the sensor unit with the 1-element Fresnel lens array. (b) Data from the sensor unit with the 5-element Fresnel lens array. (c) Data from the sensor unit with the 11-element Fresnel lens array. (d) Probability density distributions of the clusters in (c).

Fig. 3.8 The clustering results for 120 data sets from the sensor unit placed at the height of 120 cm. (a) Data from the sensor unit with the 11-element Fresnel lens array. (b) Probability density distributions of the clusters.

Fig. 3.9 The clustering results for 120 data sets from the sensor unit placed at the height of 35 cm. (a) Data from the sensor unit with the 11 Fresnel lens array. (b) Probability density distributions of the clusters.

Fig. 3.10 The identification results for a sensor unit with an 11-element lens array at the sensor-object distance of 2m. (a) The sensor unit is placed at the height of 120 cm. (b) The sensor unit is placed at the height of 80 cm. (c) The sensor unit is placed at the height of 35 cm.

Fig. 3.11 The identification results for a sensor unit with the 11-element lens array at the sensor-object distance of 3m. (a) The sensor unit is placed at the height of 120 cm. (b) The sensor unit is placed at the height of 80 cm. (c) The sensor unit is placed at the height of 35 cm.

Fig. 3.12 The identification results for the registered objects and unregistered objects at the same rejection threshold. (a) Recognition results for two registered objects: Bob and Jason. (b) Rejection results for two unregistered objects.

Fig.3.13 A sensor module (including a PIR detector, a Fresnel lens array, Texas Instrument micro-controller (MSP430149) and RF transceiver (TRF6901) module)

Fig.3.14 The experiment setup for real-time walker recognition.

Fig. 3.15 Flow chart of real-time feature extraction.

Fig. 3.16 Event window detection from windowed power spectrum density of sensory data. (a) Raw data. (b) WPSD of the raw data. (c) Digitized signals. (d) Event windows.

Fig.3.17 The modified diagram of the real-time recognition process.

Fig. 3.18 Two event data sets generated by two different individuals.

Fig. 3.19 The spectral features for two different individuals derived from the event data in Fig. 3.18.

Fig.3.20 Each column is for different speed levels. Each subfigure contains 40 superimposed data sets.

Fig.3.21 Results for leave-one-out cross-validation of calibration data.

Fig.3.22 The supervised clustering results upon 3 labels for 120 data sets with contours of the probability density distributions. (a) From Jason's training data. (b) From Bob's training data.

Fig.3.23 The RMSEP results for different value of additive noise.

Fig.3.24 ROC curves of four registered people.

Fig. 4.1 A sensor module (Model 4M) and its visibilities that associate detection regions and the four sensors.

Fig. 4.2 The diagram of the identification process.

Fig. 4.3 The experiment setup.

Fig. 4.4 Event signal generation. (a) The response signals of a PIR detector. (b) Filtered signals. (c) Digitized signals. (d) Binary signals. (e) Event signals.

Fig. 4.5 Two 4-bit digital features (event index sequences) generated by two subjects walking along the same path.

Fig. 4.6 The corresponding decimal sequential signals of Fig. 4.5.

Fig. 4.7 The flow-chart diagram of digital feature extraction.

Fig. 4.8 Log-likelihoods of (a) five walkers' testing data against one walker's HMM; (b) one walker's testing data against five walkers' HMMs.

Fig. 4.9 Two sensor modules and their visibility matrices that define the detection regions of the four sensors. (a) Model 4L; (b) Model 4H.

Fig. 4.10. Average path-dependent identification rates as a function of the number of persons for the three types of sensor modules.

Fig. 4.11 Three sensor modules with 8 sensor units and their visibility matrices that define the detection regions of the eight sensors. (a) Model 8L; (b) Model 8M; (c) Model 8H.

Fig. 4.12 Average path-dependent identification rates as a function of the number of persons for the three types of sensor modules.

Fig. 4.13 Average identification rates for a group of 10 as a function of the (a) training sequences in different length; (b) testing sequences in different length.

Fig. 4.14 Average path-independent identification rates as a function of the number of persons.

## List of Tables

Table 2.1 Summary of characteristics of Fresnel lens array.

Table 3.1 Summary of identification false alarm rates with different sensor configurations.

Table 3.2 The recognition results of 4 registered and 6 unregistered subjects. During the experiment, each subject walks 20 rounds along a fixed path. The detection of unregistered subject yields a report of “Others”.

Table 4.1 Closed-set path-independent identification results for 10 walkers.

