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符合人類視覺觀感之數位影像自動化版調重製技術

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作者簡介

我是史宜平，目前就讀於北一女中三年級數理資優班。自幼便對數理有極大的興趣，曾於全國科展獲得數學科第三名，也曾參加台大的高中物理科學人才培育計畫。個性活潑，喜歡接觸新事物，興趣為素描、寫作、吹奏單簧管。

有幸於高一下學期開始至中研院資訊科學研究所的多媒體技術實驗室，接受廖弘源教授及學長姊的指導，非常喜歡資訊科學以及多媒體研究這個領域，每當幫他人解決電腦問題時總讓我感到十分開心，也希望自己的專題研究能為影像處理的發展盡一份小小的心力。

摘要

由於硬體設備的限制，許多人眼可察覺的景物細節經由數位相機呈現後，其亮度對比便被壓縮而不易辨識。因此我們撰寫演算法，透過局部性版調重製，使影像細節之亮度對比高於人眼的恰可辨識差，並建立基於人類視覺觀感之量化方法驗證演算法成效。本技術能放大數位影像被壓縮亮度對比的部分，有效增加影像中之可視細節，與前人的研究相比，不論在細節或顏色飽和度的呈現皆有較好的成果，且能全自動處理數位影像，達節省人力之功效。本技術可應用於改善曝光不正確之數位影像、協助刑事偵辦、增強醫學影像、還原老照片及改良硬體設備。

Human Visual System-based Automatic Tone Reproduction

Abstract

In this report, we propose an effective scheme for enhancing the visual details of digital images automatically. Digital archives are becoming increasingly popular because of the development of convenient and powerful digitizing techniques. However, due to the lack of sufficient dynamic range of modern sensor technology, many details of digital images are compressed and become imperceptible to human eyes. To solve this problem, we propose a local tone reproduction algorithm to enhance the visual details automatically, which makes local contrast of digital images higher than the human just-noticeable-difference and simultaneously compresses the noise of images. In our scheme, we combine a local normalization concept with an adaptive contrast assessment process. The proposed tone reproduction scheme effectively enhances poor quality regions, while preserving good quality regions with default parameter settings. We also propose an evaluation method based on human visual system to calculate the percentage of visual details of the enhanced images. The result shows that our technique reveals the visual details of an image effectively. Furthermore, the enhanced images have not only more visual details but better color saturation than the results of Reinhard's algorithm. This technique can be applied to the improvement of digital image which is under/over exposure, criminal investigation, enhancement of medical images, restoring old photos, and improving hardware equipments.

符合人類視覺觀感之
數位影像自動化版調重製技術

壹、 前言

一、 研究動機

隨著數位相機的普及，相片的品質好壞愈發顯得重要，但相機所拍得的照片卻時常無法真實呈現人眼所看到的景色。人眼的感光細胞能感受到對比約為30000:1的亮度範圍，此比例稱為動態範圍（dynamic range），也就是一個景或影像中所能表現出之最亮與最暗的對比值。除此之外，人眼具有適應能力，當環境亮度改變時能夠自行適應，逐漸看清景物。

但由於硬體的限制，相機的動態範圍比起人眼來得低，也不具有適應能力，且因為真實世界的景物亮度與數位相機拍攝後所表現出的亮度呈線性關係，與人眼所感覺到的亮度卻呈非線性關係，因此部分亮度的景物經由相機拍攝後，對於人眼來說其亮度對比便被壓縮而不易辨識。

除了動態範圍的差異，隨著拍攝的簡易性以及儲存媒體的日益龐大，大量的即時拍攝以求抓住即時的畫面已經逐漸成為大多數使用者的需求，這樣的使用習慣也使許多快速拍攝的照片曝光不甚準確，導致其細節難以辨識。

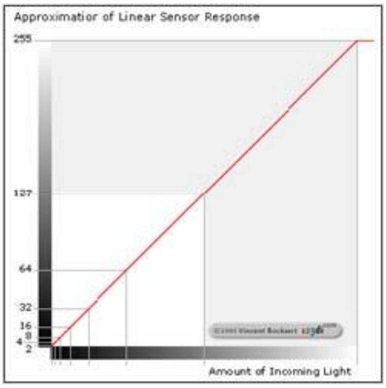
基於上述情況，我們撰寫演算法，透過版調重製（tone reproduction），放大相片被壓縮亮度對比的部分，使其容易辨識，並將所攝得的景物清楚呈現。

二、 研究目的

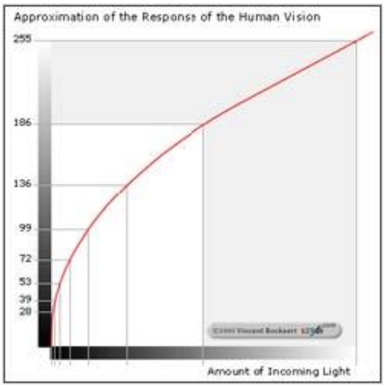
撰寫演算法，透過版調重製，放大數位影像被壓縮亮度對比的部分，使其細節能有效呈現，並利用人類視覺的特性，建立符合人類視覺觀感的系統。此系統無須使用者自行設定參數，能全自動處理數位影像，達省時及大量處理之功效。最後建立基於人類視覺觀感的有效量化方法，以驗證研究成效。

三、 文獻探討

由於數位感測器的動態範圍比人眼實際所見的動態範圍還低許多，也不像人眼具有適應光線的調整能力，且真實世界的景物亮度與數位相機拍攝後所表現出的亮度呈線性關係，但與人眼所感覺到的亮度卻呈非線性關係，如圖1所示[10]，因此許多人眼可察覺的景物細節都無法透過攝錄影器材等硬體設備呈現。



(a)數位相機實際接收到的亮度與其所感知之亮度呈線性關係



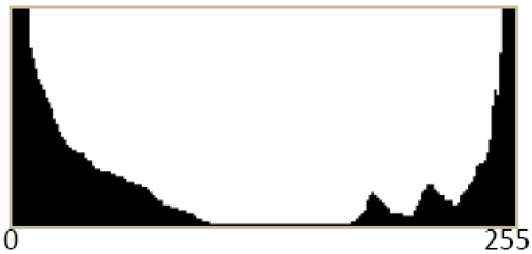
(b)人眼實際接收到的亮度與其所感知之亮度呈非線性關係

圖1

我們常以直方圖(histogram)表現景物或影像的亮暗分布，如圖2.(b)所示為例，x軸的值由0到255，代表的是像素由全黑到全白的亮度值，而y軸則是圖2.(a)所示影像中該亮度值的像素總數。

由於景物的實際動態範圍高於感測器的動態範圍，其透過硬體呈現後，亮度對比會被壓縮並且難以辨識影像細節，甚至因過度壓縮而完全損失，如圖2.(b)所示，由直方圖中可看出會有大量的像素聚集在亮部與暗部兩端。

(a) 經硬體拍攝後對比被壓縮之影像



(b) 圖(a)的亮度分布直方圖

圖2

因此，近幾年來有研究工作者提出了數個版調重製的演算法，希望能透過影像處理方法彌補硬體設備之不足。各種演算法依據影像處理的方式分成兩類：全域性(global)版調重製及局部性(regional)版調重製。

在全域性版調重製方面，Fattal等人[5]壓抑高亮度梯度並利用辨識亮度變化的方法保留住影像的細節，接著，在修改過的梯度範圍，透過解波松方程式(Poisson equation)，可以減少較大的梯度，將高動態範圍的景物轉至低動態範圍的影像。Durand等人[4]則利用雙向濾波器(bilateral filter)，將一張影像分解成兩個圖層，一張為光影變化圖層，另一張為保存能見細節的圖層，接著便減少光影變化圖層的相對應對比。為了使結果與人眼所看見的景物相似，Pattanaik等人[7]提出基於人眼適應與空間視覺的計算模型，相對於此，Drago等人[3]提出基於亮度對數壓縮的演算法，使影像的細部特徵能有效呈現，並有明顯的對比。但是現存的全域版調重製方法都有個缺點：它們都不可避免地壓抑了影像高對比的區域。

在局部性版調重製方面，Krawczyk等人[6]依據亮度將影像分解成不同的區塊並計算局部的亮度數值，Chen等人[1]則提出另一個局部處理的方法，在影像的不同區域利用對稱的技術獲得較好的影像品質。由於局部版調重製將影像的不同部份分開處理，產生的影像容易出現不自然的邊界。此外，全域及局部性版調重製方法有個共同的常見問題：兩個方法所得到的成效都受到參數設定非常大的影響。因此，我們將針對上述問題尋求最佳的解決方法。

貳、 研究方法或過程

一、 數位影像重現技術的概念

在介紹本專題研究的演算法之前，我們先整理一些數位影像處理的概念，做為設計演算法的方針。

我們將影像模型$I(x,y)$視作像素(x,y)的反射係數$R(x,y)$與明視度$L(x,y)$的乘積，如方程式(1)所示。

$$I(x,y) = R(x,y) \times L(x,y) \quad (1)$$

而增強後的影像模型$I'(x,y)$則以方程式(2)表示。

$$I'(x,y) = R'(x,y) \times L'(x,y) \quad (2)$$

假設我們以濾波器增強數位影像的細節，由於影像中過度曝光之部分會降低亮度以強化細節，而曝光不足之部分會增加亮度以強化細節，因此數位影像的整體亮度對比會降低而使其分布聚集在動態範圍的中央。

在方程式(3)中，G_{min}和G_{max}分別代表動態範圍的最小值與最大值，而δ和ϕ則為兩個大於零的常數，表示修改過後的影像亮度值不會偏向動態範圍的極值。

$$G_{min} + \delta \quad < \quad L'(x,y) \quad < \quad G_{max} - \phi \tag{3}$$

在處理數位影像前，我們將其分為S個片段以分別處理，並以$I_k(x,y)$表示，如方程式(4)所示。

$$I(x,y) = \{I_k(x,y), \quad k = 1,2,\ldots,S\} \tag{4}$$

另外，根據心理學的韋伯定律(Weber’s Law)，影像中的局部對比差異必須大於恰可辨識差(JND, just noticeable difference)，人眼才能感知其細節。因此欲增加影像的可視細節，必須增強影像的局部對比，使其大於一標準值，如方程式(5)。

$$Contrast(I_k(x,y)) > threshold \tag{5}$$

本專題研究將根據上述概念，建立符合人類視覺觀感的版調重製演算法。

二、 本專題研究之版調重製演算法

我們以方程式(6)表示版調重製演算法的主要概念，其中，$I_k(x,y)$ 與$I_k'(x,y)$分別為局部影像修改前後的亮度，我們預設為3×3的方塊，$E(x,y)$ 代表局部正規化的過程。

$$I_k'(x,y) = I_k(x,y) \times E(x,y)^{C(x,y)} \tag{6}$$

而$E(x,y)$ 的定義如方程式(7)所示。

$$E(x,y) = \frac{I_k(x,y) - I_{min,k} \times T}{I_{max,k} - I_{min,k} \times T + \varepsilon} \times \frac{G}{I_k(x,y)} \tag{7}$$

$Imax,_k$和$Imin,_k$分別是局部影像$I_k(x,y)$中的亮度最大值與最小值，T為介於0到1之間的參數，以在 $Imin,_k$ 與 $I_k(x,y)$ 十分相近時仍能維持影像的對比強度。G代表整張影像動態範圍的大小，而ε則是為避免分母為零所設的極小常數。

另外，我們設參數$C(x,y)$，以比較正規化前後影像的對比強度，其定義如方程

式(8)所示。

$$C(x,y) = Guassian\,(arg\ \{Lap(\ I_k\ )\ ,\ Lap\ (I_k')\}\ ) \qquad (8)$$

$Lap(.)$代表拉普拉斯運算子 (Laplacian operator)：$Lap(I) = \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2}$ ，我們以其來估算影像的對比強度，藉以比較原始影像與正規化影像的對比強度大小。其中，若 $Lap(\ I\ ) > Lap(\ I'\ )$，則 $arg\ \{Lap(I)\ ,Lap\ (I')\ \}=0$，$C\ (x,y)\ =0$，即 $E\ (x,y)^{\ C\ (x,y)}=1$，由方程式(6)可得 $I_k'\ (x,y) = I_k\ (x,y)$，表示若原始影像的對比大於正規化影像的對比時，我們便取原始影像的該部份做為版調重製的結果。

若正規化影像對比大於原始影像對比，即 $Lap(I)\ \le Lap(I')$，則 $arg\{\ Lap(\ I\ ),Lap(\ I'\ )\ \}\ =1$。 但如果使 $C\ (x,y)\ =1$ ，由方程式 (6) 得 $I_k'\ (x,y)\ =I_k\ (x,y)\ \times E\ (x,y)$，表示取正規化影像的該部份做為版調重製的結果，但若整張版調重製的影像皆由原始影像與正規化影像拼湊組成，局部影像間會顯得較不自然，因此我們進行高斯模糊運算，即$Guassian(.)$，使$C\ (x,y)$ 的值介於0到1之間，讓局部影像間的差異不會過大而使版調重製的結果（尤其在邊界的地方）顯得不自然。

三、 版調重製演算法之參數計算

我們根據知名相機網站Digital Camera Reviews and News所提供之SNR標準[10]，將影像中亮度差低於3的對比視作雜訊，而對比高於此強度的部分則當做應保留的細節，並試著尋找適合的參數，加強影像中應保留的細節，同時壓抑影像中的雜訊。

我們藉由恰可辨識差曲線[2]（如圖3所示），判斷影像中不同亮度的部份對於人眼是否為可視細節，同時調整正規化過程中T與ε兩個參數的值，希望能使版調重製後的影像之細節對比增強，並使雜訊強度維持在恰可辨識差之下。

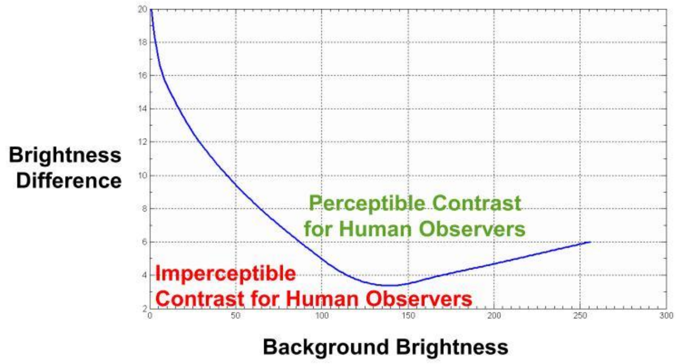


圖3 人眼的恰可辨識差曲線

經由實驗，我們發現T與ε這兩個參數與影像亮度有關，另外，當$I_k(x,y)$ 極小時，ε 的數值對於對比增強便會產生極大的影響。如圖4所示中之綠色曲線為在不同亮度的情況下所模擬出亮度差為3的曲線，而藍色曲線為該曲線經正規化後對比增強之結果，紅色曲線則表示亮度差為3的影像經增強後的對比，黑色曲線表示綠色曲線增強的梯度，由此曲線我們發現暗部的對比被增強得最多，但由於一般影像中雜訊最多的地方通常都位於暗部，暗部的對比增強程度越大，則越可能同時加強雜訊，並被人類視覺系統察覺。

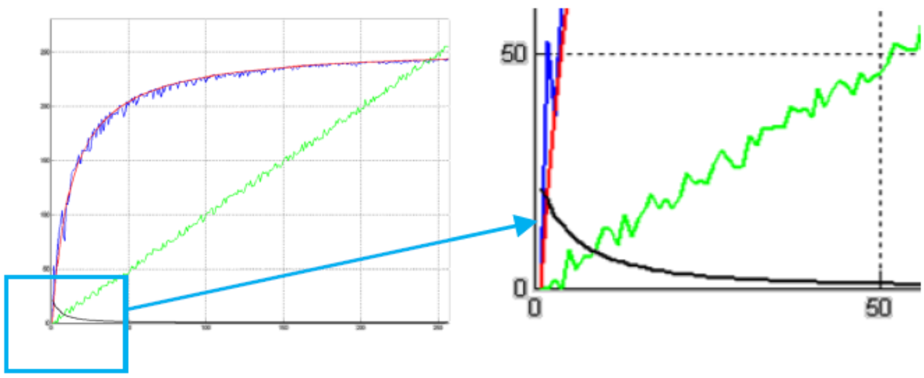
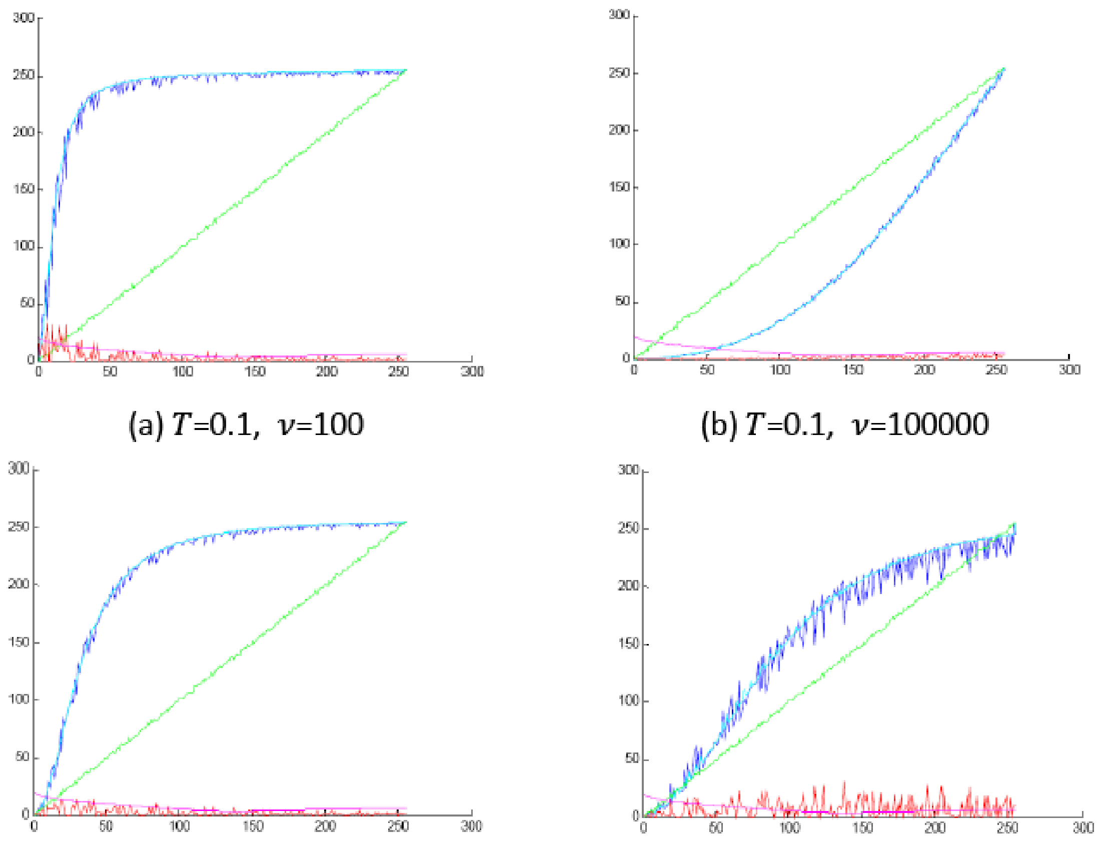


圖4

因此，我們將 ε 改為如方程式(9)所示之參數，令其為v的函數。

$$\varepsilon = v \times (s - min(s)) + 0.1 \tag{9}$$

其中，$s=1/(I_k(x,y)+1)$ 。接著，藉由如圖5所示說明不同的T值與v值設定造成的差異。



(a) T=0.1, ν=100　(b) T=0.1, ν=100000

(c) T=0.1, ν=1000　(d) T=0.9, ν=1000

圖5　在不同參數下雜訊增強的曲線

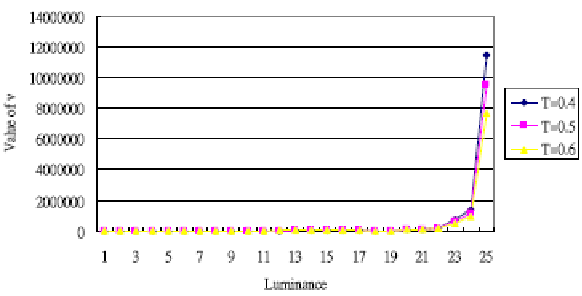
在如圖5所示中，綠色的曲線為在不同亮度的情況下所模擬出亮度差為3的曲線，而深藍色曲線為該曲線經正規化後對比增強之結果，淺藍色曲線為正規化曲線的平均值，我們將深、淺藍色曲線的差以紅色曲線表示，即亮度差為3的影像經增強後的對比，粉紅色曲線為恰可辨識差曲線，由於我們預設亮度差為3以下的部分為雜訊，因此我們希望雜訊（綠色曲線）經增強後的曲線所產生的對比（紅色曲線）能低於恰可辨識差曲線，使其不易被人眼辨識。

觀察圖5.(a)與圖5.(b)可發現，在T值相同的情況下，當ν值越小，暗部的紅色曲線起伏越大，表示暗部的細節被強化得較多；反之，當ν值越大，則亮部的紅色曲線起伏越大，表示亮部的細節會被強化得較多，由此比較可知ν值會對影像中不同亮度部分的強化程度造成影響。

觀察圖5.(c)與圖5.(d)可發現，在ν值相同的情況下，當 T=0.1，淺藍色曲線的幅度比綠色曲線大許多，表示對比增強的程度非常大。又，當 T=0.9，可看到淺藍色曲線的幅度與綠色十分相近，表示對比增強的程度並不明顯，且紅色的曲線起

伏十分大並超過恰可辨識差曲線，這個結果將使影像雜訊增強並超過恰可辨識差。為避免上述情況，使對比增強維持在適當的程度，我們便將T值設為0.5。

如圖6所示為當T值為0.4到0.6時在不同亮度情況下的v值，由此圖我們可發現圖中曲線的斜率隨著亮度的增加而驟增，使低亮度部分的曲線起伏難以辨識，因此，我們將該曲線取log，底數為2（如圖7所示中綠色曲線），使其起伏變化於圖中容易辨識，以方便我們進行曲線擬合(curve fitting)。



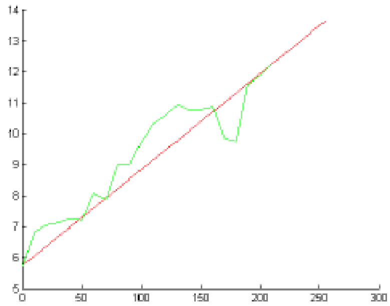


圖6　雜訊強度為3時，T=0.4到0.6的曲線　　圖7　log$v$及其經線性擬合之曲線

另外，由於雜訊曲線（如圖5所示中之綠色曲線）是由亂數模擬出的結果，因此我們利用此曲線找出的參數曲線（如圖7所示中綠色曲線）也會如亂數曲線般變動。而假使此參數的設定沒有與亮度成正相關，則會使增強後的影像產生光暈現象或亮暗對比顛倒等情況。因此，我們將實驗出的參數曲線，以最接近的線性曲線做曲線擬合，如圖7所示中之紅色曲線，並將其還原成v值曲線，如圖8所示為雜訊強度分別為3到5時之v值曲線。

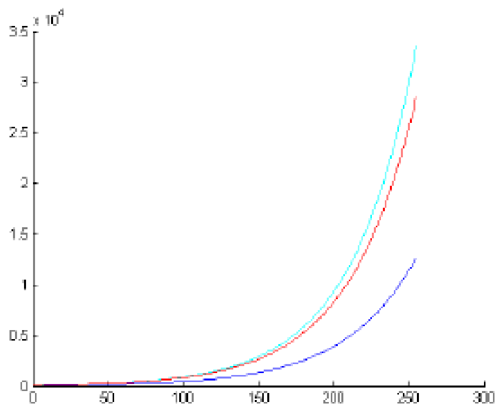


圖8　雜訊強度為3到5時的v值曲線

最後，我們根據如圖8所示中的曲線找出不同亮度下參數v的值（深藍色曲線為雜訊強度為3的情形、紅色曲線為雜訊強度為4的情形、淺藍色曲線則為雜訊強度為5的情形）。如表1所示為方程式(10)中不同的雜訊強度下之$p1$與$p2$的值。其中，$Bilateral\ (x,y)$ 為雙向濾波器，我們執行該濾波器以減輕影像邊緣光暈等不自然的現象。

$$v=2^{p1\times Bilateral\,(x,y)\,+p2} \tag{10}$$

表1

	雜訊強度為3	雜訊強度為4	雜訊強度為5
$p1$	0.03096	0.03375	0.03265
$p2$	5.737	6.43	6.477

四、 基於人類視覺觀感之量化方法

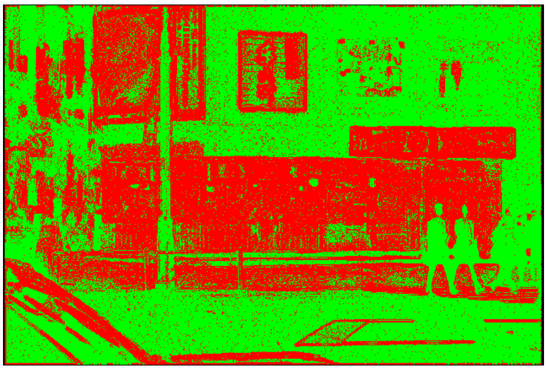
我們根據如圖3所示的恰可辨識差曲線，建立基於人類視覺觀感的量化方法以驗證本專題研究之成效。根據如圖3所示的曲線，我們將數位影像中人眼所能感知細節的區域以紅色表示，而人眼所不易感知的區域則以綠色表示，並計算紅色所佔的比例，以表示影像中可視細節的多寡。

以如圖9所示為例，在圖9 .(a)中，我們可以辨識出招牌及店家，建築物及路面等部份則較難看清細節，因此在圖9 .(c)的量化結果中，招牌及店家大致呈現紅色，而其餘細節不明顯的部分則為綠色。我們計算出紅色所佔比例為43.6025%，表示圖9 .(a)中只有43.6025%的細節是人眼可輕易辨識的。

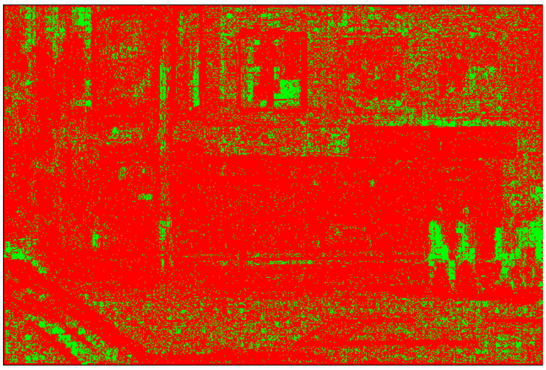
如圖9.(b)所示為圖9.(a)經本專題研究之版調重製技術處理過後之影像，可發現人眼可視細節明顯增加，而藉由圖9.(d)所示之量化結果，可得知人眼可視細節之比例已提高到83.2473%，原本如圖9.(c)所示中綠色的部分在細節增強過後也改為以紅色呈現。

(a) 原始影像

(b) 本專題的執行結果



(c) 圖(a)之量化結果可視細節比例 43.6025%



(d) 圖(b)之量化結果可視細節比例 83.2473%

圖9

參、 研究結果與討論

一、 研究結果

我們根據前述之演算法撰寫程式，並將其以圖形化界面呈現，如圖10所示。左側的影像為原始圖片，右側的影像則為版調重製後的結果。本技術為自動化版調重製，因此已提供預設參數，不需使用者自行尋找參數，但介面的右方仍可讓使用者根據不同情況的需要調整參數。

圖10　本技術之使用者介面

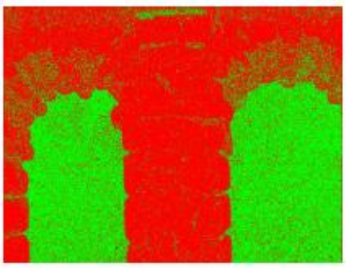
下列幾組測試資料（如圖11到圖16所示）分別為不同類型之數位影像，除了展示本專題研究之版調重製技術處理前後之影像及其量化結果，也附上Reinhard等人的演算法[8]的執行結果，將本專題研究之成效與前人的研究成果做比較。

如圖11和圖12所示可發現，Reinhard等人的演算法為增強影像暗部的對比而犧牲了亮部的細節，而本專題研究的版調重製技術不論在亮部或暗部皆能有效增加影像的細節。

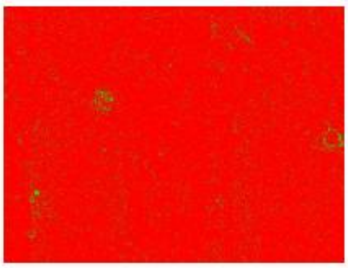
(a) 原始影像

(b) 本專題的執行結果

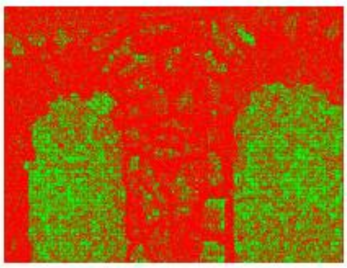
(c) Reinhard的演算法



(d) 圖(a)之量化結果可視細節比例58.5544%



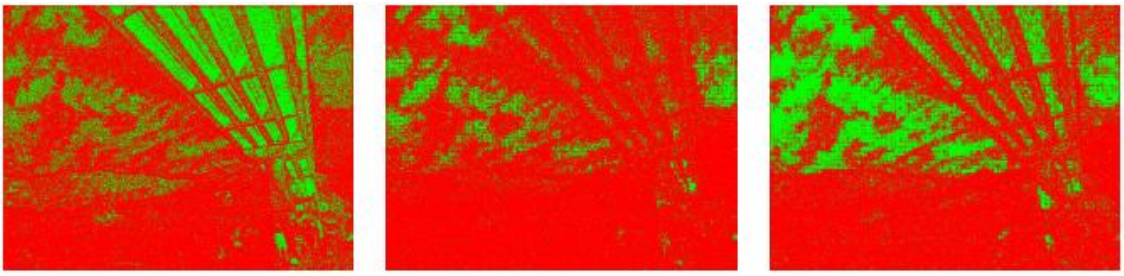
(e) 圖(b)之量化結果可視細節比例96.1696%



(f) 圖(c)之量化結果可視細節比例70.2503%

圖11

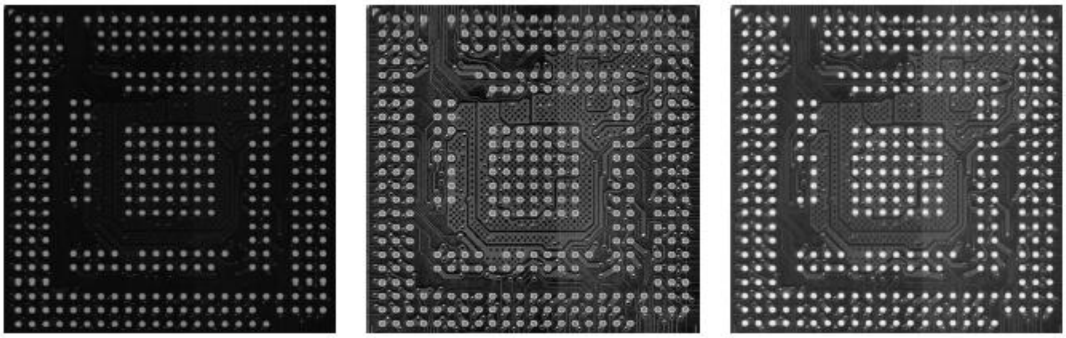
(a) 原始影像　(b) 本專題的執行結果　(c) Reinhard的演算法



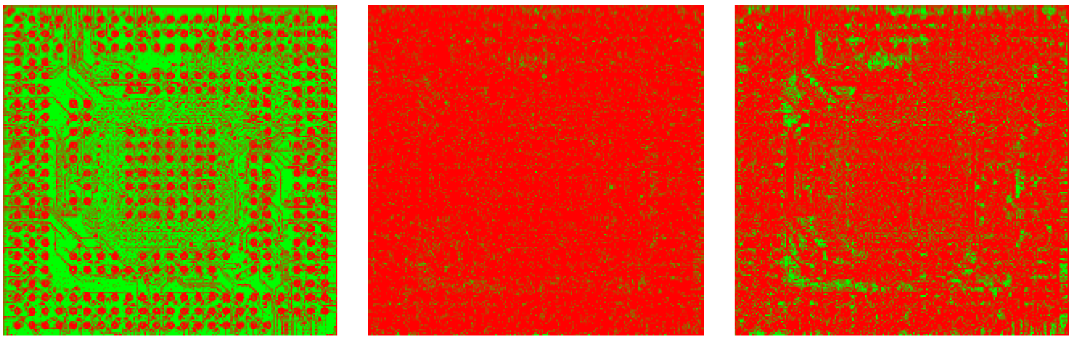
(d) 圖(a)之量化結果可視細節比例71.6654%　(e) 圖(b)之量化結果可視細節比例86.541%　(f) 圖(c)之量化結果可視細節比例72.0622%

圖12

如圖13及圖14所示為細節較多、較複雜之影像，經由量化結果可發現，本專題研究之版調重製技術比起前人的演算法更能有效增加影像中的細節。



(a) 原始影像　(b) 本專題的執行結果　(c) Reinhard的演算法



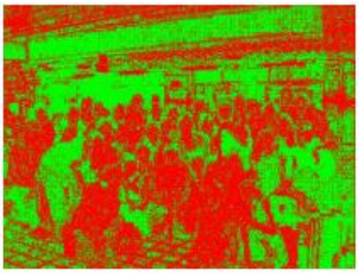
(d) 圖(a)之量化結果可視細節比例38.0056%　(e) 圖(b)之量化結果可視細節比例93.2397%　(f) 圖(c)之量化結果可視細節比例82.8864%

圖 13

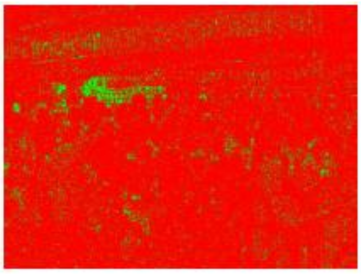
(a) 原始影像

(b) 本專題的執行結果

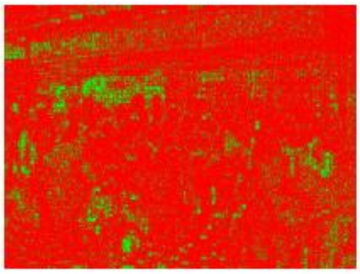
(c) Reinhard的演算法



(d) 圖(a)之量化結果可視細節比例53.0713%



(e) 圖(b)之量化結果可視細節比例91.3932%



(f) 圖(c)之量化結果可視細節比例86.2487%

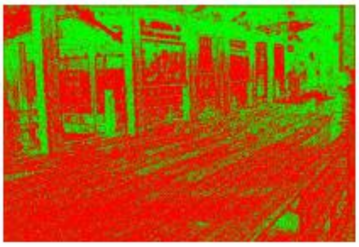
圖14

如圖15及圖16所示的執行結果可發現，除了有效增加影像中的可視細節，本專題研究的版調重製技術與前人的研究相比，執行結果有較高的顏色飽和度，使影像顏色較豐富，因此本專題研究之技術比起前人的研究有更高的可行性與實用價值。

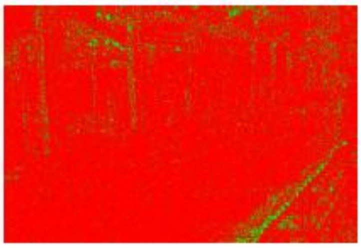
(a) 原始影像

(b) 本專題的執行結果

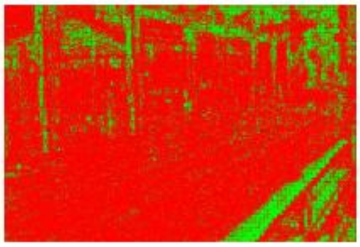
(c) Reinhard的演算法



(d) 圖(a)之量化結果可視細節比例63.493%



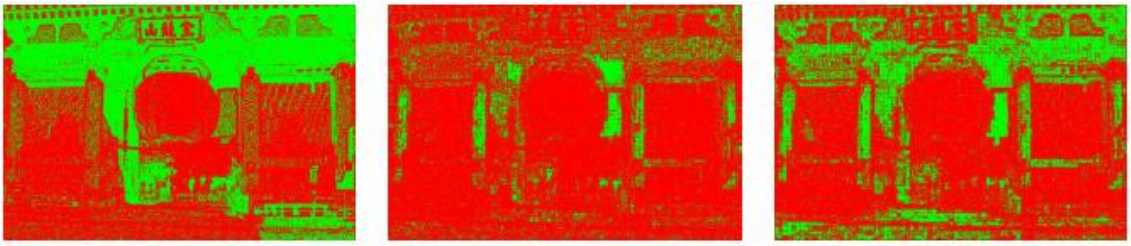
(e) 圖(b)之量化結果可視細節比例92.8242%



(f) 圖(c)之量化結果可視細節比例81.6855%

圖15

(a) 原始影像　　(b) 本專題的執行結果　　(c) Reinhard的演算法



(d) 圖(a)之量化結果可視細節比例56.7286%　　(e) 圖(b)之量化結果可視細節比例84.0464%　　(f) 圖(c)之量化結果可視細節比例69.5729%

圖16

二、 討論

1. 亮部細節會減少

由實驗結果發現，當遇到大面積相似的亮部區域時，版調重製後的結果會發生可視細節減少的現象。如圖17所示中，原本不易辨識的暗部雖得到改善，但比較圖17 .(c)與圖17 .(d)發現，天空部份的可視細節卻較原始圖片少。

經討論過後，應是因為本技術之參數設定在亮度高的地方所增強的細節並不多，又經高斯模糊處理過後便會降低其對比。因此未來持續改進本技術成效時，針對原始圖片對比並不明顯之區域，將嘗試不進行高斯模糊處理，以避免減少影像細節。

(a) 原始影像　　(b) 本專題的執行結果

圖 17

續下頁

(c) 圖(a)之量化結果可視細節比例38.8124%

(d) 圖(b)之量化結果可視細節比例52.6099%

圖 17(繼續)

2. 比較不同參數設定下的執行結果

本技術的使用者介面提供三種參數讓使用者自行依需要調整，分別為雜訊強度、版調重製強度及濾波器大小。

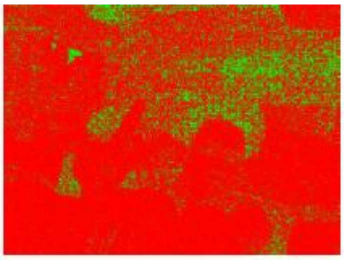
雜訊強度表示將亮度差為多少以下的對比視作雜訊。雜訊強度設得越大，表示在版調重製的過程中會有越多的細節被視作雜訊而被壓抑。系統預設值為3，圖形化界面提供3到5的值供使用者選擇，如圖18所示為雜訊強度為3和5的執行結果。在原始影像品質較不佳，即雜訊較多時，雜訊強度較大可避免版調重製後的影像強化過多的雜訊。

(a) 原始影像

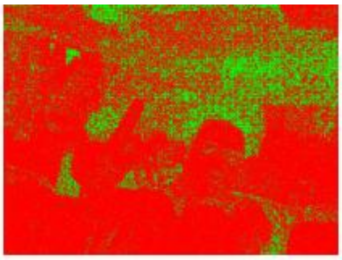
(b) 雜訊強度為3

(c) 雜訊強度為5

(d) 圖(a)量化果可視細節比例29.9651%



(e) 圖(b)量化結果可視細節比例84.6761%



(f) 圖(c)量化結果可視細節比例78.9458%

圖18

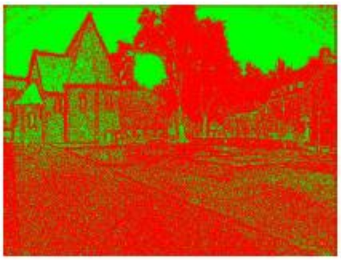
版調重製強度即表示演算法中$C\ (x,y)$ 的最大值，此參數的變動範圍介於0與1之間。系統預設值為1，圖形化界面提供0.8到1的值供使用者選擇。由於此參數直接影響了$E\ (x,y)$ （即正規化過程）的大小，因此我們藉由調整此參數控制版調重製的強度。

以如圖19所示為例，可發現當$C(x,y)$為1時，其所增強的可視細節最多，接著便隨著$C(x,y)$範圍的縮小而減少。另外，由於版調重製的過程會使像素的亮度往動態範圍的中央聚集，因此版調重製的強度越大，整張影像的亮度分布會越平均。而由於版調重製的強度也代表細節增強的程度大小，因此版調重製強度越大，影像中細節的色彩也會越飽和。基於以上情況，我們提供了0.8到1的值，供使用者在不同的狀況下自行調整參數。

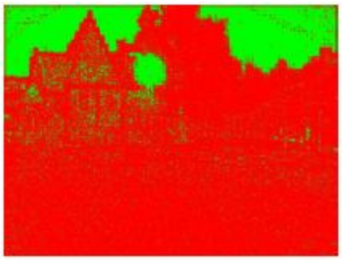
(a) 原始影像

(b) $C\ (x,y)$最大值為0.8

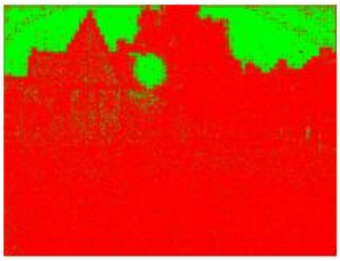
(c) $C\ (x,y)$ 最大值為1



(d) (a)圖量化結果可視細節比例61.6924%



(e) (b)圖量化結果可視細節比例79.8014%



(f) (c)圖量化結果可視細節比例82.403%

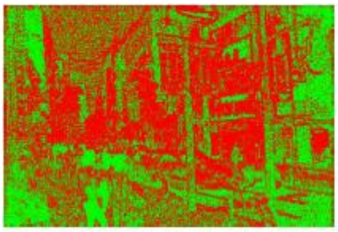
圖19

濾波器大小即表示演算法中之$I_k\ (x,y)$ 為幾乘以幾的方塊。根據實驗，我們發現濾波器越小，則可處理之影像細節也越小，可以增強細部的對比；反之，若濾波器越大，則可保留影像整體之亮暗對比。而隨著濾波器增大，影像處理所需之時間也隨之增加，所能增強之細部細節則越來越少，如圖20所示。因此，我們預設將濾波器大小定為3像素，以有效增加影像細節。

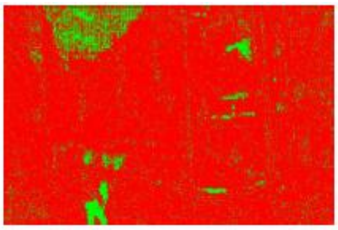
(a) 原始影像

(b)濾波器大小為3像素

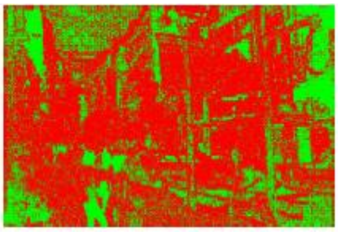
(c)濾波器大小為50像素



(d) 圖(a)量化結果可視細節比例56.9402%



(e) 圖(b)量化結果可視細節比例89.786%



(f) 圖(c)量化結果可視細節比例67.6951%

圖20

肆、 結論與應用

一、 結論

本專題研究所提出之版調重製技術的確能放大數位影像被壓縮亮度對比的部分，有效增加影像中之可視細節，並建立基於人類視覺觀感之量化方法驗證其成果，與前人的研究相比亦有較好的成效。且無須使用者自行設定參數，能全自動處理數位影像，達節省人力及大量處理之功效。

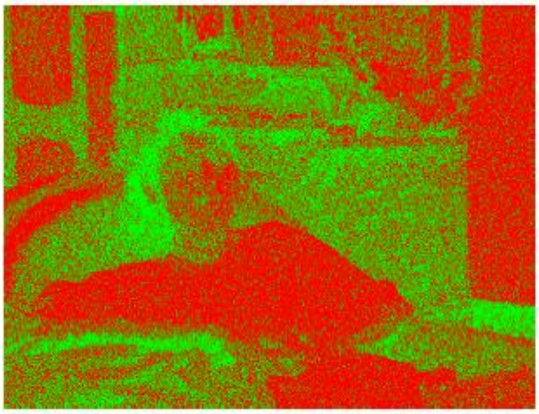
二、 應用

1. 改善曝光不正確之數位影像

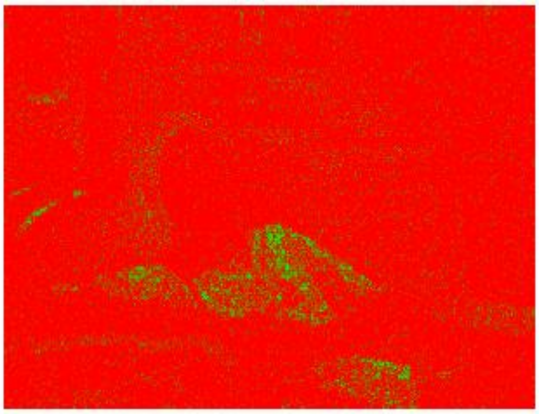
隨著數位相機的普及，影像品質的好壞愈顯重要，也大幅提升了數位影像處理技術的實用性。由於拍攝簡易性及儲存媒體的日益龐大，大量的即時拍攝以抓住即時的畫面已經成為大多數使用者的需求，這樣的使用習慣也使許多快速拍攝的照片曝光不甚準確，以致產生許多部分細節曝光不足或是過度曝光的照片。本專題研究之技術可有效改善曝光不正確之影像，且介面操作方便、不需使用者自行設定參數，因此可供一般大眾廣泛使用於生活中（如圖21所示）。

(a) 原始影像

(b) 本專題的執行結果



(c) 圖(a)之量化結果可視細節比例 9.0947%



(d) 圖(b)之量化結果可視細節比例 94.319%

圖21

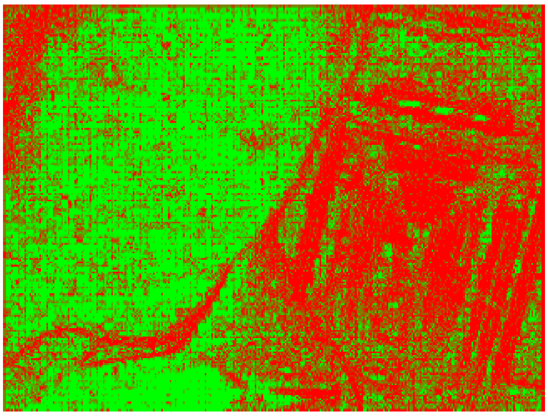
2. 協助刑事偵辦

監視器所錄製之畫面時常是協助警方偵辦案件的重要要素，但因為硬體設備限制、物體背光、環境光線不足等因素，監視器所錄製的畫面常會過暗而不易辨識。將影片中之畫面擷取出來後，可利用本專題研究之技術強化影像細節（如圖22所示），以協助刑事偵辦。

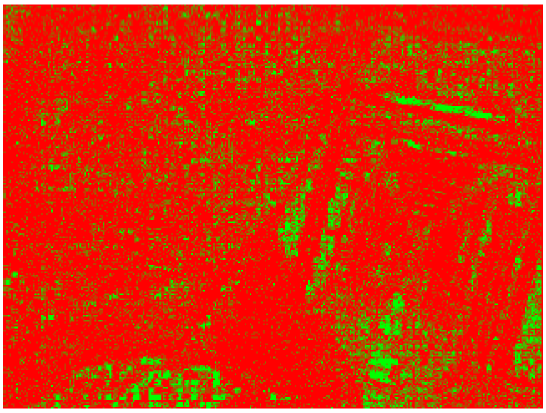
本技術在刑事偵辦方面的應用還有指紋辨識。指紋的紋理十分複雜，經警方採集後不一定每部份的細節都十分清楚，本研究可用於處理採集之指紋影像，增強其細節以協助比對。

(a) 原始影像

(b) 本專題的執行結果



(c) 圖(a)之量化結果可視細節比例 47.3026%



(d) 圖(b)之量化結果可視細節比例 83.8704%

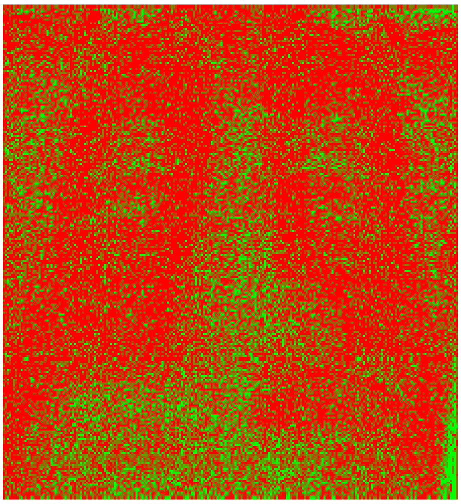
圖22

3. 增強醫學影像

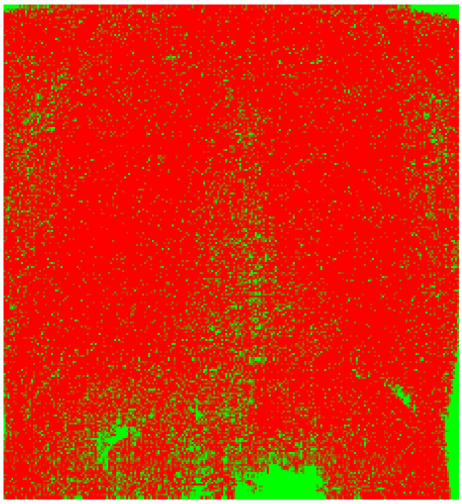
現今之醫療體系常使用X光及超音波等檢查程序，以其所取得之影像判斷患者的健康情形，若沒有及時發現患者身體的異狀，可能會錯失其治療時機而造成無法挽回的遺憾。本專題研究之版調重製技術可用以處理醫學影像（如圖23所示），增強其細節，協助醫療人員及時有效地判讀醫學影像。

(a) 原始影像

(b) 本專題的執行結果



(c) 圖(a)之量化結果可視細節比例 73.7693%



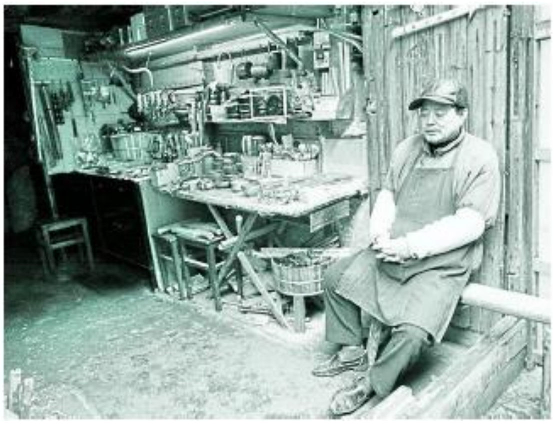
(d) 圖(b)之量化結果可視細節比例 87.7399%

圖23

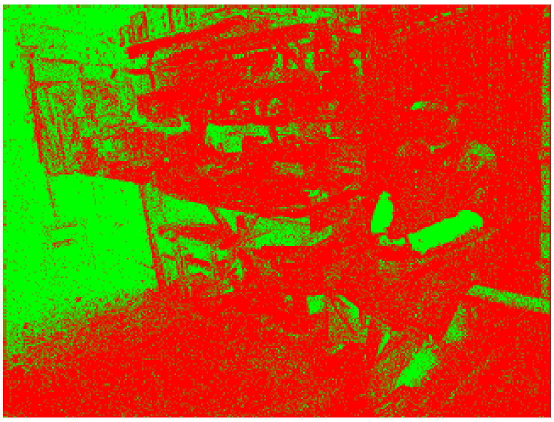
4. 還原老照片

本專題研究之技術可以運用在數位典藏國家型計畫所收錄的數位老照片上。這些照片受限於當時的硬體設備，品質並不佳，再加上拍攝年代已很久遠，許多景物都無法再重新取得及拍攝。透過本專題研究的版調重製技術，可以將部份數位化老照片原本不清晰的細節給重現回來，如圖24所示。因此，本專題研究對國家文化產物的保存會有實質的貢獻。

(a) 原始影像



(b) 本專題的執行結果



(c) 圖(a)之量化結果可視細節比例 69.8242%

(d) 圖(b)之量化結果可視細節比例 90.0736%

圖24

5. 改良硬體設備

本專題研究之技術應可植於攝錄影器材之晶片中，在硬體拍攝後直接進行影像處理，以增進硬體設備之功能，並節省拍攝完再進行影像後製的人力及時間。

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[10] http://www.dpreview.com

評語

此作品在增加一張影像的細節。它應用 Local 的方式。此作品完整（包括演算法提出，與相關演算法的交互比較）。此作品可應用在許多方面（例如醫學影像）。

有以下建議可更增加其完整性：

1. 如何找出最佳 filter Size 的大小。

2. 測試更多的圖像。

Abstract

An effective tone reproduction scheme is proposed to restore imperceptible details of digital images. Due to the lack of sufficient dynamic range, some details of digital images may be invisible to human eyes. Here, we propose a novel method which combines a local normalization process with a global contrast balance process. In the local normalization process, each local contrast of an image was dynamically expanded based on the characteristic of each local region; self-adaptive parameters are set based on the concept of human visual system. The global contrast balance process can ensure better image quality with self-adaptive parameters. An evaluation metric based on human visual system was defined to judge the performance of the proposed method. The experimental results showed that the proposed method can improve images of different dynamic ranges. With minimal requirement of manual adjustment, this technique has the capability of processing massive data.

Human Visual System-based Adaptive Tone Reproduction for Restoring Imperceptible Details of Digital Images

1. Introduction

Insufficient dynamic range and fast changing illumination environment are the most challenging issues for the development of new sensor technology. Usually, images/videos taken either under-exposure or over-exposure may easily lose their visual details. The dynamic range of an image means the range of grey values that can be utilized by the image. Due to the advancement of semiconductor technology, the available dynamic range of digital cameras becomes much larger in recent years. For an image captured by modern digital camera, to apply dynamic range mapping to recover its visual details is not difficult because it has broader intensity range. However, for some digitized aged pictures which were taken long time ago, the situation would be completely different due to the limited available dynamic range that could be used. Among the large number of visual detail recovering mechanisms, tone reproduction provides a way of mapping scene luminance with high luminance range to image with limited intensity range. The characteristic of this technique is that it can render a vivid image just like viewing a scene in the real world.

A number of techniques have been developed in the past[1-3]. For example, Erik et al.[1] proposed a method which adopts a computational model of photoreceptor behavior to help solve the tone reproduction problem. In [2], Drago et al. proposed a tone reproduction scheme based on logarithmic compression of luminance values. Their technique basically imitates human’s response to light. Fattal et al.[3] anipulated the gradient field of a luminance image by attenuating the magnitudes of rge gradients. Then, a low dynamic range image is produced by solving a Poisson equation on the modified gradient field. In general, the objective of the existing tone reproduction techniques is to map a scene with broad illumination range to display devices that only contain limited intensity range. To deal with different types of images, we present a new tone reproduction scheme which can map a scene with large illumination range property to small intensity range counterparts.

The new approach that we proposed is a hybrid tone reproduction scheme which combines a local normalization process with a global contrast balance process. In the local ormalization process, the contrast of a local region in an image is dynamically expanded based on the characteristics of the local region. Local parameters are automatically determined based on the constraint set by the human just-noticeable-difference(JND) curve. That is, to suppress the effect of noises, the noises that are enhanced simultaneously with useful data cannot exceed the value set by the JND curve. In the global contrast balance process, the system selects pixels with higher contrast from either the original or the normalized image as the result. These pixels are simultaneously balanced by automatically determined parameters. A JND-based evaluation metric is defined to judge the performance by computing the percentage of visual details of a processed image. The experiment results indicate that the proposed method is able to recover much more visual details than existing methods. Furthermore, with minimal requirements of manual adjustments, this technique has the ability to automatically process massive data.

2. Tone Reproduction and Contrast Enhancement

2.1 Discrimination between visible details and noises

Usually the purpose of post-processing a photograph is to remove noises while retaining original visual details. However, it is somewhat difficult to distinguish useful visual data from noises. Therefore, we introduce a visual detail assessment mechanism based on the JND[4] profile(also termed the Weber's curve) to overcome this problem. Using the JND profile as the judging criterion one can determine whether the content of an image is visible to human eyes or not. Using this profile,one can also calculate quantitatively the percentage of visible contents. Figure 1. shows the JND profile of the human visual system. The x-axis represents the intensity value of the background, and the y-axis indicates the brightness difference(i.e., contrast). One thing to be noted is that at different background intensity values the human visual system may have different sensitivity on contrast. According to the JND profile illustrated Figure 1., when the background intensity is low, the value of contrast that can be seen by the human eyes is much higher than when background intensity value is close to 150. To calculate the contrast value of every pixel in an image, we apply the Laplacian operator to do the job. Since each pixel of an image has its own intensity value, one can then check the JND profile to see whether it is visible based on its associated contrast value.

Since the perceivable contrast can be evaluated by the JND profile, the unnecessary noise and the useful details in images may be processed separately. We propose two primary guidelines in our algorithm: increasing the degree of detail visibility and reducing or minimizing the noise effect. To distinguish useful details and noise signal in images, noise degree is set as 3 based on the statistics reported in [5], and the visual details below this degree is considered as noise. The main idea can be explained using Figure 2. The green curve in Figure 2. represents the gradients of average luminance using signal sampled when the intensity degree of added detail is equal to 3; the blue curve represents the enhanced signal of the green curve; the cyanine curve is the average luminance degree of enhanced signal (blue curve); the red curve is the difference of blue and cyanine curve; and the pink curve represents the curve of JND threshold. The red curve can be considered as the enhanced contrast of detail degree 3. To ensure an amplified noise imperceptible, the enhanced contrast of noise curve (red curve in Figure 2.) should be always below the JND curve.

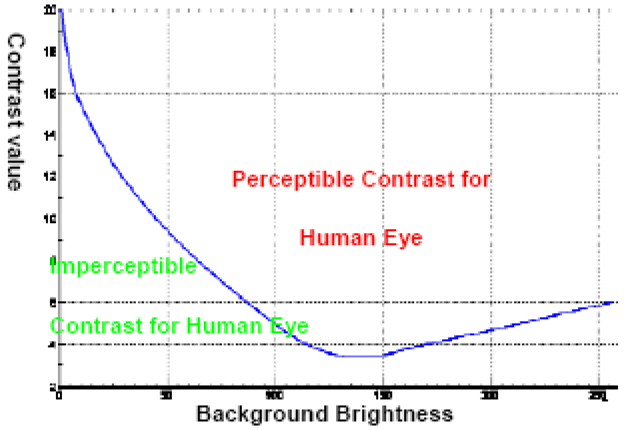


Figure 1. JND profile of the human visual system.

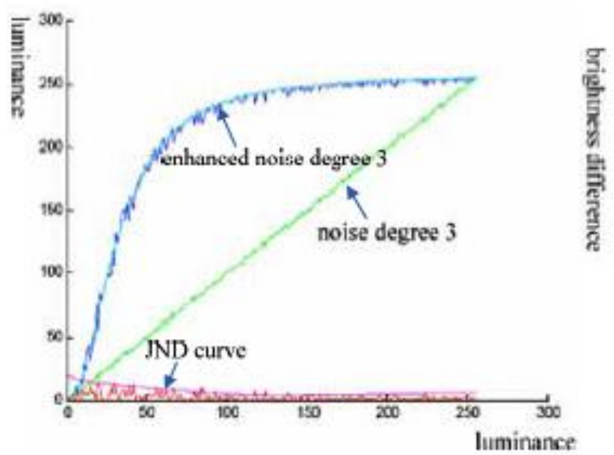


Figure 2. Relationship of enhanced noise and JND curve.

2.2 The Algorithm

The proposed tone reproduction algorithm consists of two primary stages—local normalization and global contrast balance, which can be expressed as follows:

$$I'(x,y)=I(x,y)\times E(x,y)^{C(x,y)} \quad , \tag{1}$$

where $I'(x,y)$ is an enhanced image signal. $E(x,y)$ is the local normalization ratio kernel. Hence, $I(x,y)$ is normalized by multiplying by the ratio $E(x,y)$. An exponential factor $C(x,y)$ is set to make the result composed of original and normalized pixels, and balance the selected pixels adaptively. Figure 3. shows how above-mentioned crocesses work.

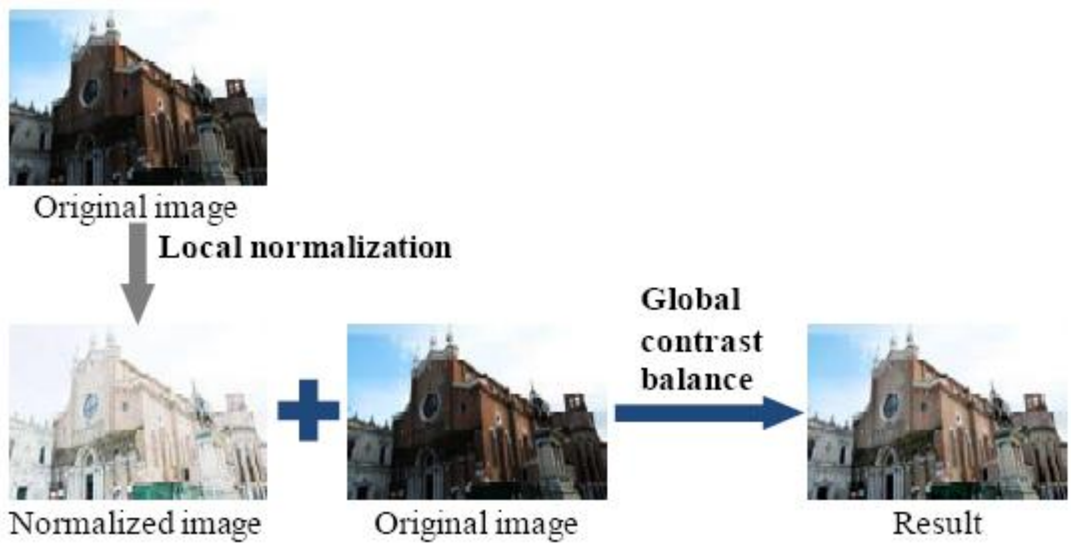


Figure 3. Flowchart of the proposed method.

In the normalization stage, an image is locally normalized to enlarge local low contrast and fit the dynamic range of display device. Since the details of some regions may be lost during the local normalization process, the contrast balance process compares each normalized pixel with the corresponding original one, and selects the pixel with higher contrast to be the result. This process can enhance local low contrast and simultaneously preserve original high contrast regions. Furthermore, the parameter setting based on the principle of reducing noises and revealing useful details are all self-adaptive. The process of our scheme is just like photographers do in manual image enhancement. In the next section, we will elaborate the proposed algorithm.

2.2.1 Local normalization

The basic idea of local normalization technique is to normalize the distribution of the image intensity to extend the full dynamic range of the images. We develop a 3×3-sized local normalization filter which can first adjust the range of an image to lie between 0 and 1, and then multiply the ratio to recover the dynamic range and rearrange the image intensity. The design of the local normalization kernel *E(x,y)* is as follows:

$$E(x,y) = \frac{I(x,y) - I_{\min} \times T}{I_{\max} - I_{\min} \times T + \varepsilon} \times \frac{G}{I(x,y)} , \tag{2}$$

where I_{max} and I_{min} are, respectively, the local maxima and minima of a target image; G is the full size of the dynamic range in a target mapping image, and ε is an offset to prevent divided-by-zero situation. An attenuation ratio T is added to multiply the local minimum intensity which can avoid unwanted effects. Figure 4. shows the normalized signals in various T. The green curve represents the original signal, and the blue curves represent the normalized signals in various T. We set the range of T from 0 to 1, and the effect of gradient reversal may occur when T is not added (T = 1). Besides, observe normalized signals when T lies between 0.1 and 0.9. As T increases, the signals are enhanced less. Therefore, a small T should be chosen for larger enhancement image signals. However, T = 0.1 is not an appropriate choice in another situation. We will discuss an appropriate value while considering the parameter ε. As to divided-by-zero parameter *ε*, it will dominate when *I(x,y)* is low according to extensive experiments. To prevent noise signals in dark regions from being enhanced seriously, we make *ε* an adaptive value:

$$\varepsilon = v \times (s - \min(s)) + 0.1, \quad where \quad s = 1/(I_k(x,y)+1). \tag{3}$$

where 0.1 and 1 are respectively added to prevent zero *ε* and divided-by-zero situation. Parameter s makes *ε* inversely proportional to the intensity *I(x,y)*, and the scale value *v* is used to control *ε*. Now, *ε* becomes a function of *v*. We choose *ε* and *v* carefully to make enhanced noise signals below the JND curve at different luminance levels. According to the experimental results, the enhanced signals at different luminance levels are proportional to *v*, and *T* influences the degree of signals that can be enhanced at different luminance levels. Therefore, we illustrate the curves between different luminance levels and *v* at various *T* as shown in Figure 5. When *T* = 0.1, there are no appropriate *v* (*v* always equals to 1) at high luminance levels, that is, noise signals and useful signals are both enhanced and they are all below the JND curve. Besides, a large *T* is not an appropriate choice because the signals are enhanced slightly when *T* is too large. Hence, we set *T* as 0.5. We use an equation to approximate the curve *v*, which is defined as follows:

$$v = 2^{p_1 \times I(x,y) + p_2}, \quad where \quad p_1 = 0.03096 \quad p_2 = 5.737 \quad , \tag{4}$$

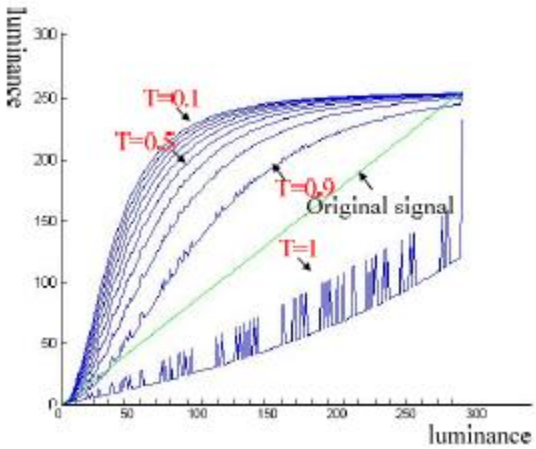


Figure 4. Enhanced signals when T lies between 0.1 and 1.

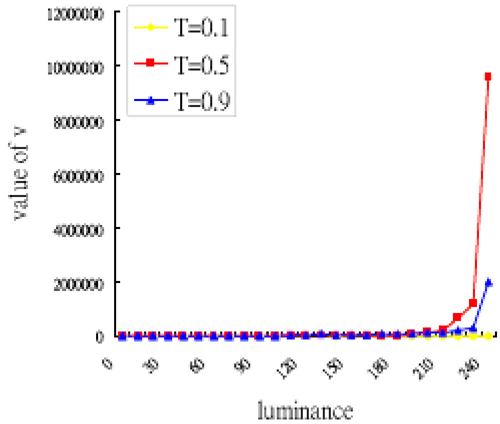


Figure 5. Curve of v in various T.

2.2.2 Global contrast balance

After the local normalization process, the exponential factor *C(x,y)* is set to make the result composed of original and normalized pixels, and balance the selected pixels adaptively. This self-adaptive contrast assessment factor *C(x,y)* is defined as follows:

$$C(x,y) = Guassian(arg\{Lap(I_k), Lap(I_k{}')\}), \qquad (5)$$

where arg{a, b}= 0 when a>b, and arg{a, b}=1 when a ≧ b; The Laplacian operator Lap(.) is used to estimate the contrast intensities of original and enhanced pixels; Gaussian(.) denotes the Gaussian operator which is used to make *C(x,y)* change smoothly. The initial setting of *C* is 0 or 1 which can adaptively select either original or enhanced pixel with higher contrast to be the result. Then it was observed that the bigger the value of *C* is, the lighter the image brightness will be (as shown in Figure 6.), so the original image brightness has to be taken into account while setting the value of *C*. Therefore, the value of *C* is set as follows when the contrast of enhanced pixel is higher than the original one:

$$C = 1 - \frac{ceil(original\_bg/50)}{10} \quad , \qquad (6)$$

where *original_bg* represents the background luminance of an original image; *Ceil(X)* rounds the elements of *X* to the nearest integers towards infinity. With self-adaptive parameter *C*, the proposed tone reproduction method can automatically improve poor quality regions of an image, and simultaneously preserve original nice details.

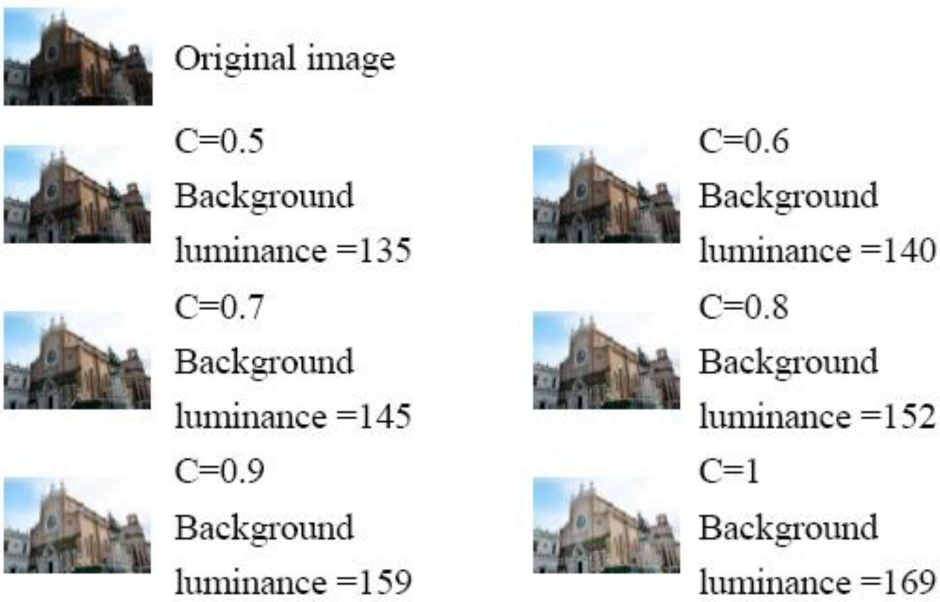


Figure 6. Enhanced images with various C.

2.2.3 Evaluation metric

We defined a novel metric based on JND curve to compute the percentages of visible local contrast of an image; the contrast above JND curve is defined as visible contrast. For example, in Figure 7., the visible details of (a) are denoted in red as shown in (b), and the invisible details are denoted in green. By calculating the percentages of red regions, we can evaluate the visual details of Figure 7.(a) as 43%. With this metric, we can judge the performance and analysis the data of this technique. The experiments are shown in the next section.

(a) (b) 43% (visual details)

Figure 7. The proposed evaluation metric based on JND curve.

3. Experimental results

In these experiments, we used images of different dynamic ranges to show the effectiveness of our approach. We compared our results with those respectively processed by Reinhard and Devlin's algorithm and histogram equalization algorithm(HE).

As shown in Figure 8., we processed a scanned aged picture, which is a low dynamic range image, and compared the enhanced image with the result of HE algorithm, which is widely used to adjust low contrast images. Our method can maintain the original luminance distribution characteristic and avoid raising noise level, while HE algorithm may inevitably enlarge image noise and show unnatural color tones. Furthermore, the enhanced images showed that not only photos taken by digital equipments can be restored. After being scanned into computers, aged photos can also be enhanced effectively by this program.

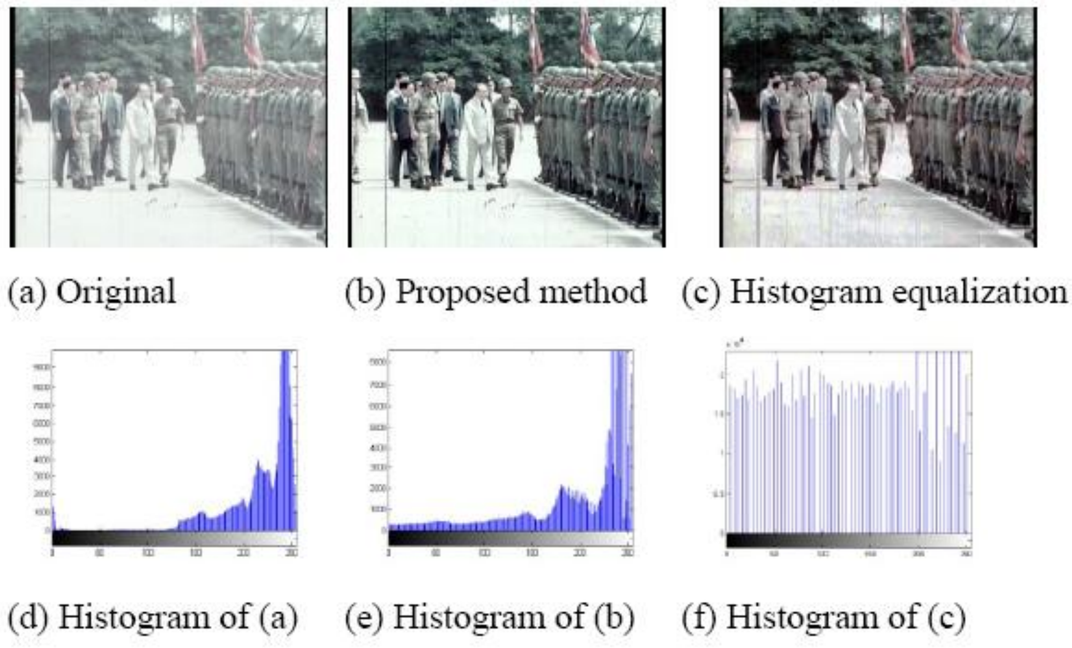
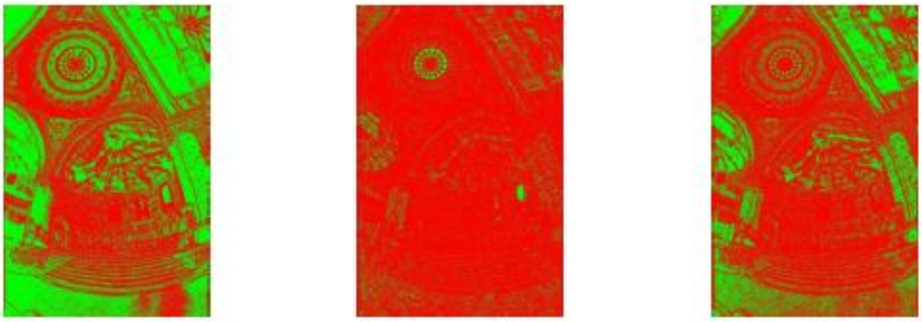


Figure 8. The experimental results of a low dynamic range image.

∗(a), (b) and (c), respectively show the original image, the enhanced image by applying our method and image enhanced by HE algorithm.(d), (e) and (f) are histograms of Figure 8. (a), 8(b) and 8(c), respectively.

In the following experiment, we used an HDR image to compare our results with those processed by Reinhard and Devlin’s algorithm. Since the Reinhard and Devlin’s algorithm requires the selection of parameters, we tried to choose a set of parameters that best fits their algorithm. The result shows that the enhanced image of our algorithm has more perceptible details than the result of Reinhard and Devlin’s algorithm.

(a) Original | (b) Proposed method | (c) Reinhard and Devlin



(d) The percentage of perceptible details = 52% | (e) The percentage of perceptible details=90% | (f) The percentage of perceptible details=71%

Figure 9. The experimental results of the HDR image.

＊(a) shows an original image, (b) and (c) show the image reproduced by applying our algorithm and the Reinhard and Devlin’s algorithm,respectively. (d), (e) and (f) show the percentage of visible details of (a), (b) and (c), respectively.

The test data in Figure 10. is a common digital image, i.e., a low dynamic range image.The details of our result image are more than the result of Reinhard and Devlin’s.Furthermore, the sky is still blue after applying our algorithm, in the contrary, he blue sky in the Reinhard and Devlin’s result is washed-out because of over enhancing the light regions in the image. It is showed that our method can effectively improve original local low contrast of an image, and simultaneously preserve original nice details.

(a) Original (b) Proposed method (c) Reinhard and Devlin

Figure 10. The experimental results of the LDR image.

∗(a), (b) and (c) are the original image, the result of our method and then result of Reinhard and Devlin’s algorithm, respectively.

4. Conclusion

Due to the limit capabilities of display devices, the aspects of digital images may be lost through compression. To restore those compressed details, we proposed a self-adaptive tone reproduction system, which is based on the concept of human visual system, and can ensure better image quality. The proposed method combines a local normalization process with a global contrast balance process to improve original local low contrast and simultaneously preserve original nice details. A novel metric was also defined to evaluate the visibility of an image and judge the performance of this technique. The experimental results showed that the proposed method can effectively improve images under different dynamic ranges. The enhanced images have more visual details and are better than the results of recent studies. With minimal requirement of manual adjustments, this technique has the ability of processing massive data. Furthermore, with the capability of enhancing images of various dynamic ranges, our method can be applied to preserve digitized historical archives.

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