ニューラルネットワークを用いた 分光学的カラー画像理解のための 並列処理システム —その植生モニタリングへの応用—

(10555013)

平成10年度～平成12年度科学研究費補助金(基盤研究(B)(2))
研 究 成 果 報 告 書

平 成 13 年 3 月

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はしがき

色彩は外界の分光学的情報を担っており、対象物の性質を判断する上で非常に重要な情報源である。色は元来人間の視覚で認識される感覚である。色情報から観測対象に含まれている情報を客観的かつ正確に収集するためには、色の原因である分光学的な記述法にもとづく解析が必要になる。画像を対象とする場合は、多数の狭帯域フィルタを通して観察した多重分光画像は取り扱うデータが膨大な量になり、その収集、処理、伝送などに多大な負担がかかることが避けられない。通常は得られた膨大なデータに対して、主成分分析などの多変量解析手法をもちいて、必要とされるデータを選択的に抽出する、などの方法がとられる。

それに対して、本研究で新たに提案した広帯域フィルタシステムにおいては、対象とする色の分光反射率をあらかじめ測定しておき、これをデータベースとして、フィルタ関数の最適化を行う。このようなフィルタを物理的に実現することができれば、それらフィルタを通して観察した画像の強度は、フィルタ関数と観察物体の分光反射率の内積に相当する。すなわち、従来は画像のピクセルごとに得られたスペクトルデータに対する解析を、最適化フィルタを通して観察するだけで、並列的に瞬時に内積演算を済ませることができる。したがって、比較的少数の画像を収集するだけで、分光学的に必要な情報を得ることができる。フィルタ最適化は、教師信号無しニューラルネットワークの一つである、自己組織化マップ（SOM）を用いた。フィルタ実行システムは、次の２方式３種類のシステムを提案し、そのプロトタイプを試作した。

（１） アクティブ型スペクトル合成光源

（２） パッシブ型広帯域フィルタシステム

- 液晶空間光変調器とリニアバリアブルフィルタを用いたシステム
- 液晶チューナブルフィルタを用いたシステム

マンセル色票の分光反射率分布を学習データとして、フィルタ最適化を行い、これら３種類のシステムを通して、色物体の観察をおこなった。４枚のフィルタ画像からスペクトル再生をおこない、３１枚の多重分光画像による計測結果と比較検討をおこなった。

研究期間内には主としてマンセル色票の分光反射率データをデータベースとして実験が行われたが、平行して草木の植生の環境汚染等による影響が調べられた。微妙な葉の分光反射率変化が認められた。今後の課題として、これら自然物分光反射率をデータベース化し、非可視域を含む、計測対象に最も相応しい帯域でフィルタ最適化を行うことができれば、対象物体に固有の感度特性を有する知的な分光画像認識システムが可能になるであろう。

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研究経費

平成１０年度	9,400 千円
平成１１年度	2,500 千円
平成１２年度	1,400 千円
計	13,300 千円

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(3) 特許出願

豊岡　了　分光画像撮像装置　(特願 2000-037642)

ABSTRACTS OF RESEARCH PROJECT, GRANT-IN-AID
FOR SCIENTIFIC RESEARCH (2001)

1. RESEARCH INSTITUTE NUMBER : 12401
2. RESEARCH INSTITUTION : Saitama University
3. CATEGORY : Grant-in-Aid for Development Scientific Research (B)(2)
4. TERM OF PROJECT : April 1998-March 2001
5. PROJECT NUMBER : 1 0 5 5 5 0 1 3
6. TITLE OF PROJECT : Parallel Processing System for Spectroscopic Understanding of Color Images by Neural network and its Application to Vegetation Monitoring

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9. SUMARY OF RESEARCH RESULTS

A spectral image include huge volume of data. Multi-variable analysis is usually used to extract important information in the image. On the contrary in the proposed system, important spectroscopic information in the images which we want to investigate is taken in advance in a learning phase and installed in a system as optimized filters. Filter optimization by self-organized map is discussed. Three proto-types of broad-band filtering systems to implement optimize filter functions which include liquid-crystal devises and optical components were constructed. Experimental results of spectral reconstruction from four filtered images by proposed system were compared with measured results by conventional method. A new intelligent eye which is applicable to vegetation mitoring will be expected.

１０. KEY WORDS

(1) Neural Network, (2)Spectroscopic image analysis, (3)Broad band filtering system, (4)Vegetation monitoring

目　　次

1．はじめに

分光画像認識はリモートセンシングをはじめとする環境センシング、医用画像における診断、顕微鏡画像の認識など、広い分野でその重要性を増している。従来の分光認識システムにおいては、分散型やフーリエ分光等の方式の違いはあるものの、いずれもはじめに分光強度を測定し、その後に多変量解析などの必要なデータ処理を施す必要がある[1,2]。データ収集過程には何らかの走査や多チャネル検出が不可欠になる。一方、ヒトの色認識機構においては、網膜の錐体にある分光感度の異なる３種類の色覚細胞が外界の光を受光し、反対色変換を行った後、脳内に蓄積されたデータベースとの何らかの相関を計算することによって色を認識する[3]。ユニーク色に特に強く反応し、同調や対比など興味ある視覚現象をもたらす。「色」は人間の視覚で認識される感覚であることから、主観的な要素が強い。このように、人間の感覚は外界の情報を満遍なく取得するのではなく、自分に必要かつ関心がある情報のみを選択的に獲得している。したがって、色についても、人によって感じ方が違って当然である。３種類の色覚細胞で受光するシステムは、本来多次元ベクトルとして記述されるべきスペクトル情報を３次元空間に圧縮している、ということもできる。

分光画像認識システムにおいても、色覚のようにシステムにとっての重要度に応じた重み付けをした上で効率的にデータ収集することができないだろうか。システムが自ら学習し、得られた知識をシステムのパラメータとして内蔵することによってこれが可能になる。そのことにより、対象に応じて帯域を広く、または狭くすることができ、非可視域を含む広い波長帯に拡張することができる。このように、低次元データからスペクトルを推定するための方法として，主成分分析[4]やWiener推定法[5]がよく用いられる。フィルタ関数最適化法としては、自己組織化ニューラルネットワークの方法も用いられる。このようにして、従来法とは違った知的な分光画像認識システムが実現するのではないか。本研究では、対象に応じて観測帯域内で波長ごとに重みをつけたフィルタを備えたシステムを考案し、マンセル色票の分光反射率をデータベースとする空間で、その有効性を確認した。さらに、本研究の応用分野である環境センシングに関しては、特に植物の葉の分光反射率の環境負荷による影響を調べるための基礎的なデータ収集をおこなった。

2．フィルタ関数の最適化法

2.1 主成分分析によるスペクトルデータの直交展開[4]

我々が日常目にする物の分光反射率は、可視域において一般的になだらかな分布を持っている。言い換えると、多様な色彩に対応するスペクトル分布は互いに強い相関がある。このように、統計的に強い相関関係にある多変量に対しては、主成分分析を中心とした多変量解析法が有効である。分光画像解析においても、ピクセルごとに得られた分光スペクトル分布に対して主成分分析を施すことにより、情報の損出を最小限にしてデータ圧縮を行うことができ、観測対象の分光学的認識や分類、さらには画像に含まれる物質の同定や状態の判定などの作業が行われる。

いま、対象とする物体の反射（または透過）光強度を、波長λ_1からλ_nの間のn点でサンプリングしたとすると、分光強度は形式的に次式の列ベクトルで記述できる。

$$\tau(\lambda) = [\tau(\lambda_1), \tau(\lambda_2), \ldots \tau(\lambda_n)]^T \qquad (1)$$

ここで、Tはベクトルの転置をあらわす。反射強度は一般になだらかなスペクトル分布を持つことから、(1) 式で表されるような多くの物体の反射強度は互いに強い相関があると考えられる。いま、(1) 式で表されるようなN個の強度データを収集したとすると、次式のような相関行列Rが定義される。

$$R = \sum_{i=1}^{N} \tau_i(\lambda)\tau_i(\lambda)^T \qquad (2)$$

行列Rの固有ベクトルは互いに直交しており、上位p個の固有値に対応する固有ベクトルを基底ベクトルとして、サンプルベクトルを近似的に展開することができる。

$$\tau' = BB^T\tau \qquad (3)$$

ここで、行列Bの列が基底ベクトルになる。

ここでは、マンセル色票1269色の反射強度に対して主成分分析を適用した結果を紹介する。マンセル色票[6]は、色の明度を縦軸にとり、それに直交する断面の円周方向に色相、半径方向に彩度をとった色立体の各位置における色の標準サンプルである。マンセル色票すべてについての分光反射率データは、フィンランドのヨエンスー大学が公開しているデータベースを使うことができる[7]。

一例として、マンセル色票1269色の反射強度に対して計算した上位8個の固有ベクトルを図1に示す。p個の固有値の全固有値に対する比を寄与率と定義すると、図1の8つの固有ベクトルの寄与率は99.99%である。図1の意味するところは、マンセル色票のすべての分光反射率をこれら8つの基底ベクトルの線形結合として記述できる、ということである[8]。展開の各項の係数は、基底関数と物体のスペクトル分布の内積（$B^T\tau$）である。図で第1基底ベクトルは展開の第1項、すなわち直流成分で、学習データ全体の平均挙動を表しており、正の要素のみから成っている。第2項以下は交流成分であり、正負の要素を含んでいる。もし、図1に示す基底関数に相当するフィルタを物理的に実現することができれば、そのフィルタを通して観察したデータは内積値に対応している。しかし、負の要素を含むフィルタを実現することはできない。

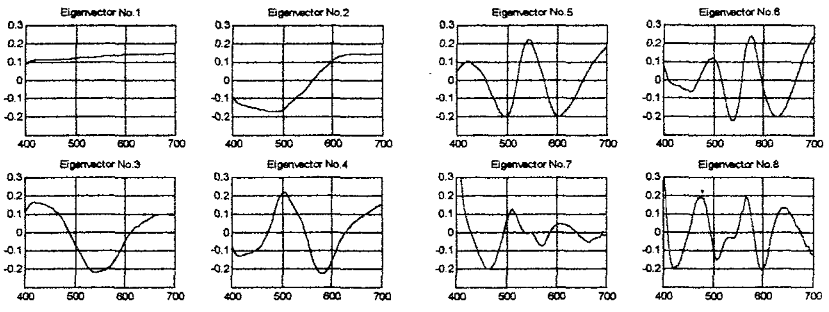


図1マンセル色表の分光反射率データをもとに部分空間法で求めた固有ベクトル

2.2 ニューラルネットワークによるフィルタ関数の最適化

フィルタ関数が満たすべき条件として、次の３点が挙げられる。

(1) フィルタの各要素は非負である、

(2) フィルタは学習データの特徴をできるだけ忠実に反映している、

(3) それぞれのフィルタは互いに独立である。

これらの条件下でフィルタ関数を最適化するために、本研究では教師信号なしニューラルネットワークを用いた。これは、データ集合をいくつかのグループに分類するクラスタリングや、データ集合のなかに隠れている特徴を抽出することなどに有効な方法であり、ここではKohonenの自己組織化マップ（Self-Organized Map, SOM）を採用した[10, 11]。SOMは基本的に図２に示すように、入力層とマップ層（ニューロン）の２層構造である。はじめにネットワークを初期化し、入力層に学習データ $x(j)$ を入力する。入力ベクトルと重みベクトル $w(i,j)$ の距離を計算する。ここで、重み $w(i,j)$ はi番目の入力とj番目のニューロンの間の結合ベクトルである。この距離が最小となるニューロンを選択し、これを「勝ちニューロン」とする。勝ちニューロンについてのみ重みを更新する（Winner Take All）。この過程を繰り返すことによって、各重み関数はお互いに最も離れた位置にあるように最適化された関数に収束していく。

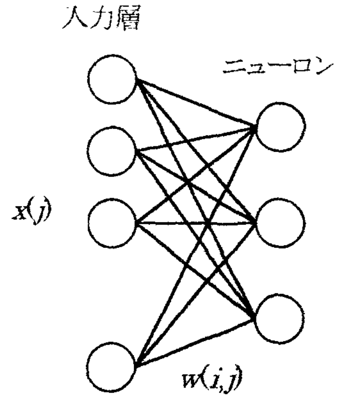


図２　SOMの構造

マンセル色票1269色の反射強度に対して計算した上位８個の最適化フィルタ関数を図３に示す[12]。図４はマンセル色票および最適化フィルタ関数をＣＩＥxy色度図上にプロットしたものである。右図の８つの点は、マンセルデータを８つにクラスタした結果とみることができ、左図に示された領域内でほぼ均等に分布している。

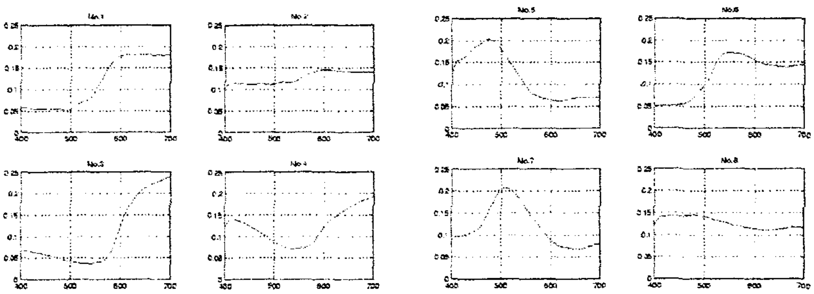


図３マンセル色票の分光反射率データをSOMで求めた８枚の最適化フィルタ関数

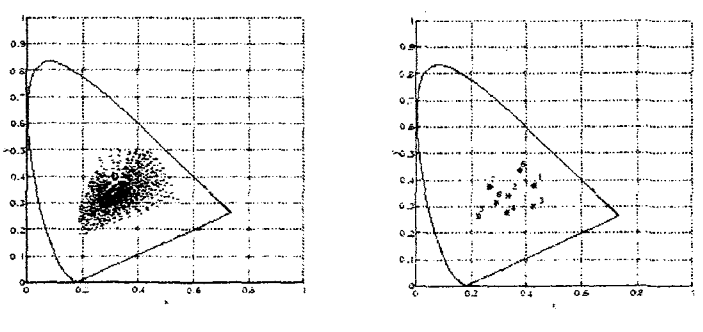
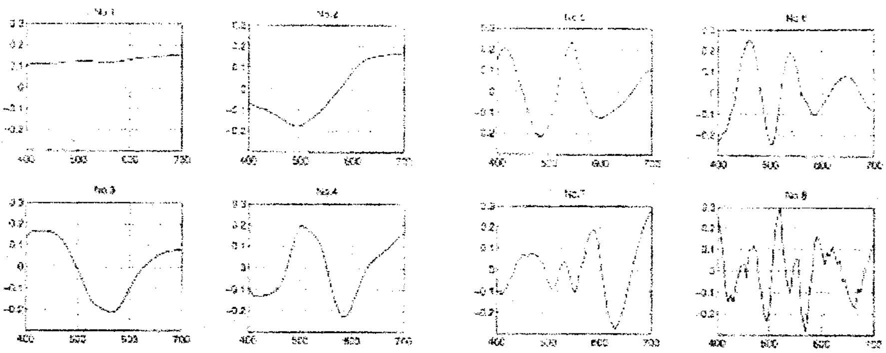


図４　CIExy色度図上にプロットしたマンセル色票（左）および最適化フィルタ関数（右）

この結果を図１に示す主成分分析の結果と比較するために、図３のフィルタ関数を特異値分解法（SVD）によって直交化した。その結果を図５に示す。



a)　　　　　　　　b)

図５　直交化フィルタ関数

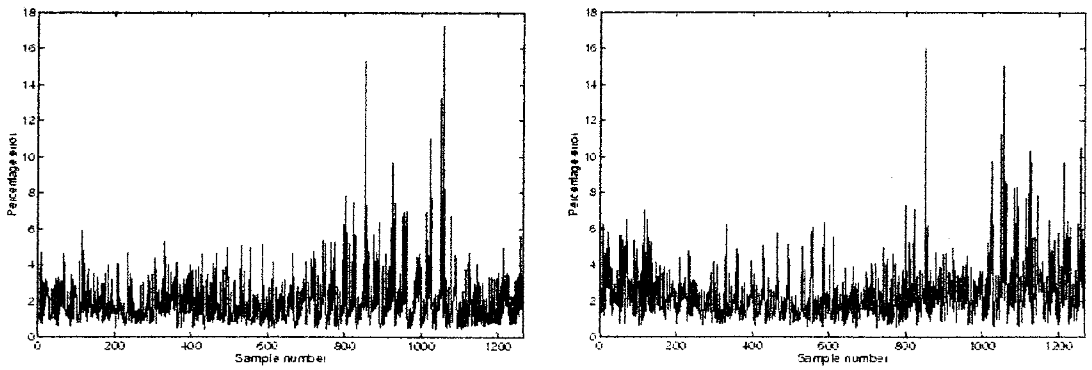
図１と図５を比較すると、１次から５次までは両者はよく似ていることに気が付く。それぞれの次数の直交関数について相関係数を計算すると、次のようになった。

0.999、0.974、0.966、0.984、0.901、-0.551、-0.361、-0.096

前半の５つの基底関数は直交化フィルタ関数と相関が強いことがわかる。5次まで採用したときの部分空間の忠実度が 99.93%であることから、これら５つの基底ベクトルがほぼデータベース全体の情報を反映しており、残りの３つの高次ベクトルはノイズを多く含んでいると考えられる。

次に、得られたフィルタ関数によるスペクトル再生を行い、部分空間法で得られた直交基底による結果と比較した。フィルタ関数行列を W とすると、サンプルベクトルは(3)式の代りに一般逆行列をもちいて次式で近似的に表すことができる。

$$\tau' = W(W^T W)^{-1} W^T \tau \qquad (4)$$



a)　　　　　　　　b)

図６　マンセルスペクトルデータベースの再生誤差

（a）部分空間法による、（b）最適化フィルタによる

ここで、$W^T\tau$ はフィルタ関数と物体の分光強度の内積であり、フィルタを通して物体を観察したときの強度値に相当する。学習に用いたマンセルデータ全てについて、(3)式および(4)式によるスペクトルの再生を行った。図6にそれらの誤差をノルム誤差 $|\tau - \tau'|$ で評価し、パーセントで表示した。図(a)は主成分分析法で作成した8次元部分空間に展開して得た結果、(b)は最適化フィルタ関数が張る空間で展開して得た結果である。横軸はサンプル番号、縦軸はノルム誤差のパーセント表示である。最適化フィルタにおける最大誤差のサンプルは、No.853、明度 2.5 の青で誤差率 16%、部分空間法では No.1058,明度 2.5 の紫で誤差率 17.3%であった。平均誤差率は部分空間法で 1.9%、最適化フィルタで 2.3%であった。図6で横軸のサンプルが 10-20 変化するたびに周期的に誤差のピークが現れている。これらのピークはいずれも明度の低いサンプルに対応している。図1と図6の比較および図6の結果から、マンセルデータベースのデータ圧縮に関しては、主成分分析と SOM による最適化フィルタはほぼ等価であるといえる。

3. フィルタ関数を実現するための広帯域フィルタシステム

前節の議論から、分光情報に基づく対象のクラスタリング等の認識を行う上では、最適化したフィルタ関数と物体の分光率の内積 $W^T\tau$を求めることが基本的に重要である[13]。前節では計算機上で内積を求めた結果を示したが、そのためには物体の分光反射率を知らなければならない。これでは、未知の物体に対して適用することはできない。ところで、実験的にはフィルタを通して観察した物体の像の強度が内積に比例することは容易に理解できる。この場合、図7に示す2つの方式が考えられる。アクティブ型においては、フィルタ関数に相当するスペクトル分布を持つ光を合成し、それによって対象物体を照明する。この方法は、実験室内で光源を用意できる環境における計測には有利である。顕微鏡画像における計測には有利である。顕微鏡画像の観察や内視鏡への応用などが考えられる。一方、野外のリモートセンシングや自発光物体の観察においては、パッシブ型が必要になるであろう。この場合、カメラの前の透過型フィルタは、最適化したフィルタ関数を実現するものでなければならない。以下にそれぞれについて筆者らが考案したシステムを紹介する。

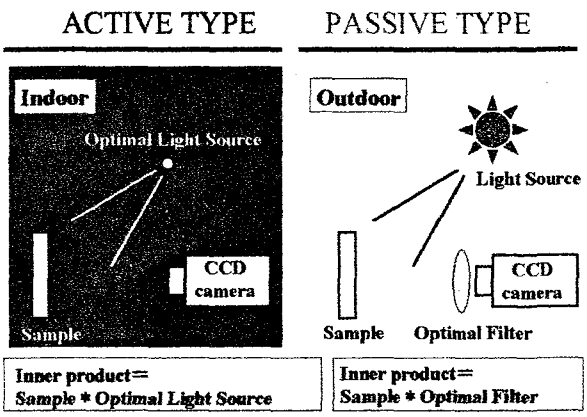


図7　アクティブ型(左)とパッシブ型(右)

3.1 アクティブ型－スペクトル合成光源[14、15]

最適化したフィルタ関数に相当するスペクトル分布を持つ光を合成する方法として、筆者らは図8に示す光学系を考案した。光源からの白色光は、スリットを経由して、凹面回折格子に入射する。コリメートされた光はここで分散され、焦点面に置かれた液晶パネルを選択的に通過し、第2凹面回折格子で混合される。出力光のスペクトル分布は、液晶パネルの透過率を制御することによって任意に設定することができる。これをスペクトル合成光源と呼ぶことにする。出力光で対象物体を照射したときの反

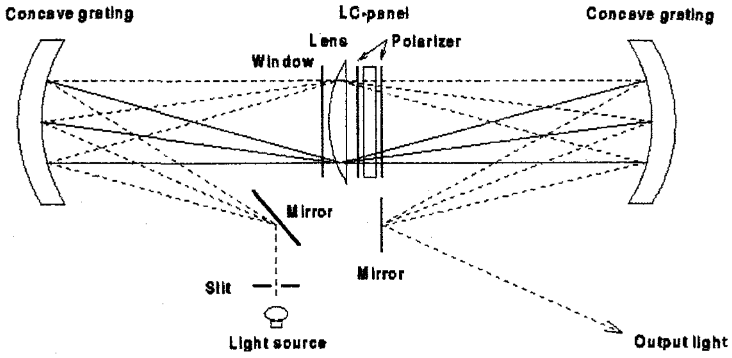


図８　スペクトル合成光源の構成

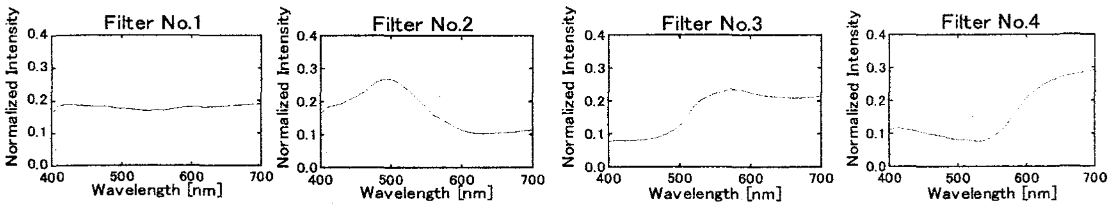


図９　マンセルデータベースによって最適化した４つのフィルタ関数

射光強度は、フィルタ関数と物体の分光反射率の内積 $W^T\tau$ になっている。

実現する光は、図９に光源のスペクトル強度を掛けたものである。図１０の点線は実現した光のスペクトル分布を測定したもの、実線は目標とする分布、図１１は光源のスペクトル強度である。No.4 のフィルタでは、強度が低いところで誤差がでたが、全体的にほぼ目標を実現しているといえる。

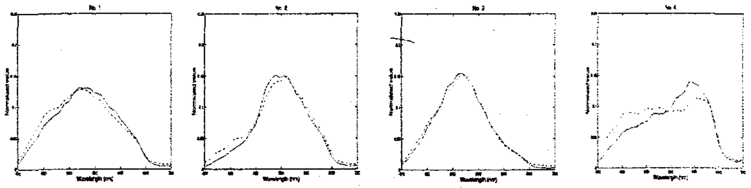


図 10　目標とする光強度（実線）および実現した光強度（点線）

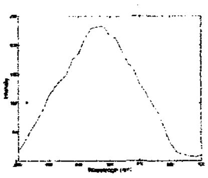


図 11　光源の分光強度

次に、このようにして実現した光で物体を照明した。観察物体はイチゴとミカンで、背景に青、緑、黄、赤の短冊を立てた。スペクトル合成光源からの４つの光で照明したときの像をモノクロ CCD カメラで撮像した像を図１２に示す。

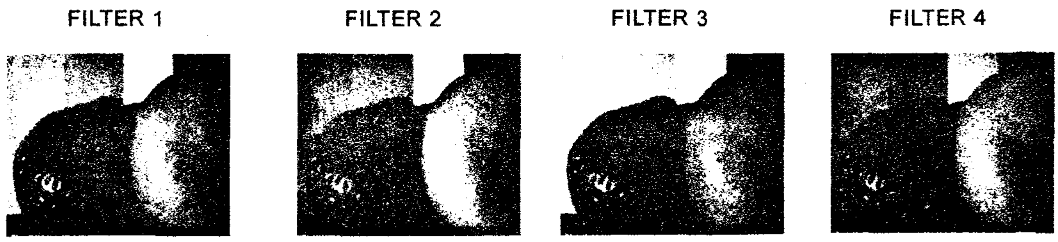
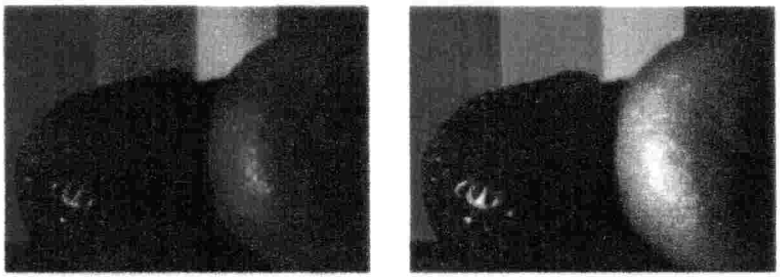


図 12　合成光で照射した物体の像

これらの画像データの各点について、(４)式でスペクトル再生を行った。その結果をRGBカラー表示した。比較のために、同じ物体を可視域（波長 400nm～700nm）を幅 10nm の帯域で３１に分割して得た３１枚の画像を通して観察したスペクトル分布をカラー表示した。それらの結果を図１３に示す。



（a）最適化フィルタ画像４枚による　（b）狭帯域フィルタ画像３１枚による

図１３　スペクトル画像から RGB 画像への変換

3.2 パッシブ型（1）液晶空間光変調器を用いた書き換え自在フィルタ [16,17]

白色光で照射された物体を、最適化された透過率分布を持つフィルタを通して観察すれば、像強度はフィルタ関数と物体の分光反射率の内積 $W^{T}\tau$ になる。この場合、透過率を自在に書き替えることのできるフィルタが必要になってくる。図１４は筆者らが考案した簡単なシステムである。フィルタ部は液晶パネル（ＬＣ）とリニアヴァリアブルフィルタ（ＬＶＦ）を貼り合わせたものをリニアステージ上に固定したものである。液晶パネルには所望のフィルタ関数に対応する透過率分布を持たせ、フレームの露光時間内に開口の直前を一定速度で掃引する。

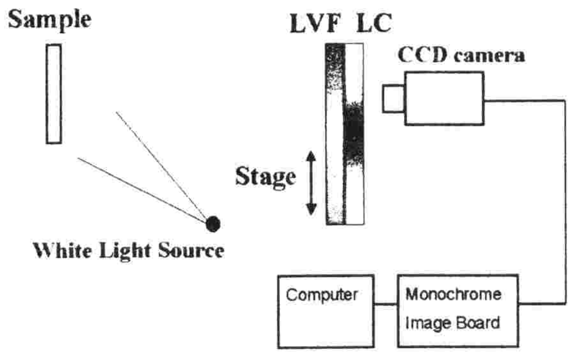


図 14　パッシブ型広帯域フィルタシステム

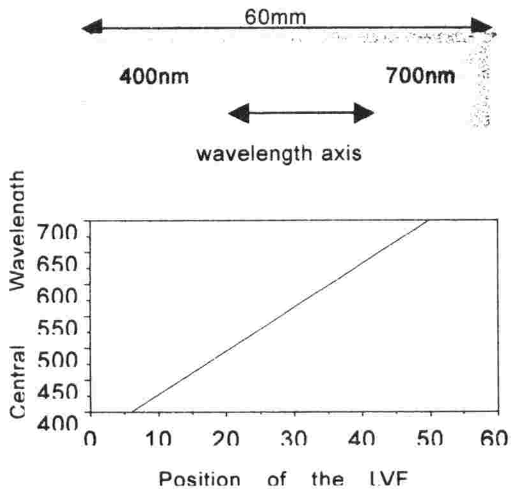


図１５　リニアバリアブルフィルタ

LVF は図１５に示すように、ガラス基板上に薄膜を蒸着した素子で、透過波長が下図に示すように、位置の関数として線形的に変化する特性を持っている。LC パネルに実現しようとする波長分布を書き込み、CCD カメラのデータ取り込み時間の間に開口部を一定速度で掃引すると、その間の積分強度は、ちょうど LC パネルに書き込んだフィルタを通したことと等価になるであろう。

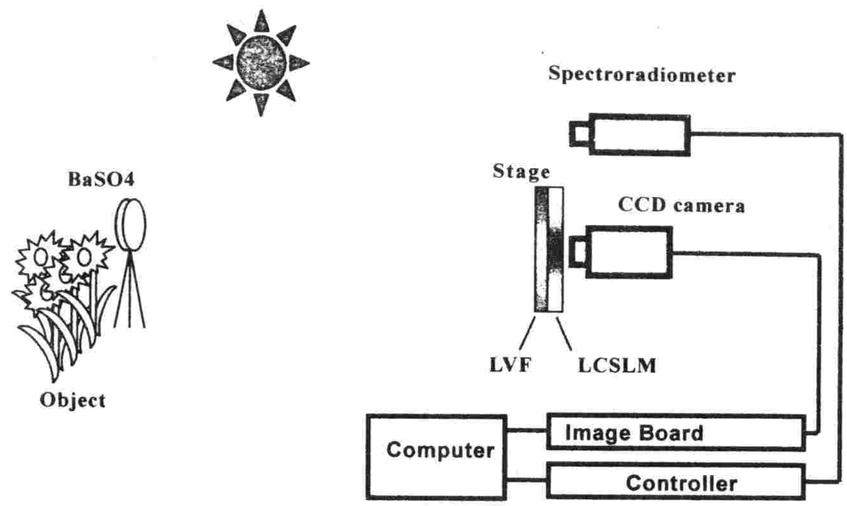


図１６　パッシブ型最適化フィルタによる太陽光照明下の草花の観察

パッシブ型の特徴は、物体照明光は広帯域に分布するものであれば何でもよいことである。ここでは、太陽光照明下にある草花の観測を行った実験の一例を示す[16]。フィルタ関数は図９を用いた。これはマンセル色標1269色の反射強度データから求めたものであり、自然物を観察する場合のデータベースとして相応しいものであるか否かの吟味は必要であろう。この点に関しては、以前の研究でマンセルデータベースが自然物をある程度反映しているとの結論を実験的に得ている[9]。今回は近似的な意味合いでこのフィルタ関数を使うことにした。実験系の概略を図１６に示す。広帯域フィルタシステムの液晶パネル（LCSLM）には図９のフィルタ関数を順次書き込み、そのつどLCSLMとLVFのジョイントを一定速度で動かし、モノクロCCDカメラで記録した。この際、太陽光の輝度は時間的に変動するので、広帯域フィルタシステムで対象物体の画像を取り込む作業と平行して、太陽光照明下にある標準白色版（$BaSO_4$）を分光放射計（オプトリサーチ社製、MSR-7000）により観察し太陽光スペクトルをモニターした。

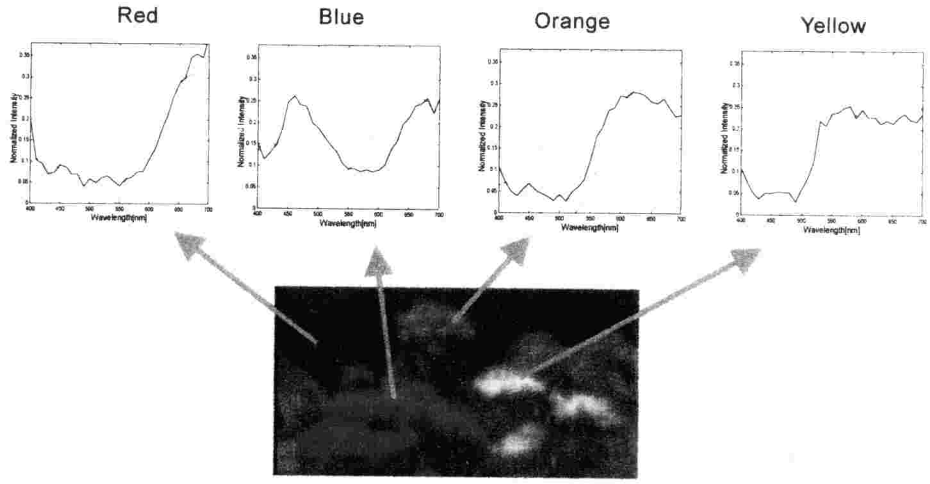


図１７　４枚の広帯域フィルタによる画像からのスペクトル再生および、
３１枚の狭帯域フィルタによるスペクトルの測定値

図１７は視野のなかの４点について、４枚の狭帯域フィルタで観察した画像に対して(10)式を適用して求めたスペクトル分布（点線）と、３１枚の狭帯域フィルタを通して測定したスペクトル分布（実線）を示したものである。広帯域フィルタによる方法は多少の誤差はあるものの、狭帯域フィルタによる測定結果とほぼ対応している。

3.2 パッシブ型（2）一液晶チューナブルフィルタ（LCTF）を用いた書き換え自在広帯域フィルタ [18,19]

前節の書き換え自在フィルタは、容易に入手できる素子を組み合わせただけで、当初の目的を達成できることがわかった。しかし、この方式では、次のような問題点があり、改善が望まれる。（１）機械的稼動部があるために、装置のコンパクト化やメンテナンスまでも考えたシステム化がしにくい、（２）液晶空間光変調器（LCSLM）のマトリクス状電極の回折像が画像ノイズとして載る。筆者らは、液晶チューナブルフィルタ（LCTF）を用いたもう一つの方法についても検討した。

LCTF（VariSpec, VIS3; 米国 CRI 社）とは、透過波長を半値幅約 5nm のガウス型帯域で 425nm~750nm の範囲で電気制御により自由に換えられる装置で、CCD カメラの開口部に装着することができる。LCTF を用いた広帯域フィルタのシステム構成は、図 18 に示す簡単なものである。LCTF の透過率の波長依存性の測定結果およびそれらを帯域毎に積分した分布を図 19 に示す。LCTF のコントロールの仕方は以下の通りである
の通りである。

LCTF の走査時間を帯域毎に制御し、CCD カメラの１回の時間の積分強度がちょうどフィルタ関数になるようにする。図２０はこの演算を模式的に書いたものである。フィルタ関数は、マンセルデータベースによるもので（ａ）に示す通りである。これを、LCTF の透過特性の積分値（ｂ）で割った結果（ｃ）を保持時間と呼ぶ。CCD カメラの露光時間に、各波長毎の保持時間を（ｃ）に示す分布で制御す

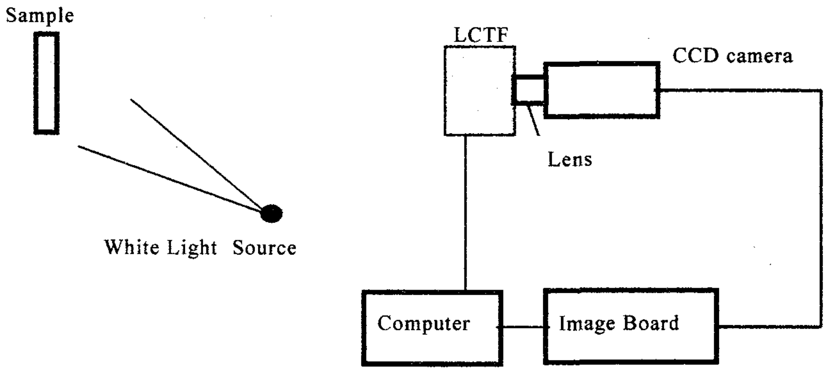


図１８　LCTF を用いた広帯域フィルタシステム

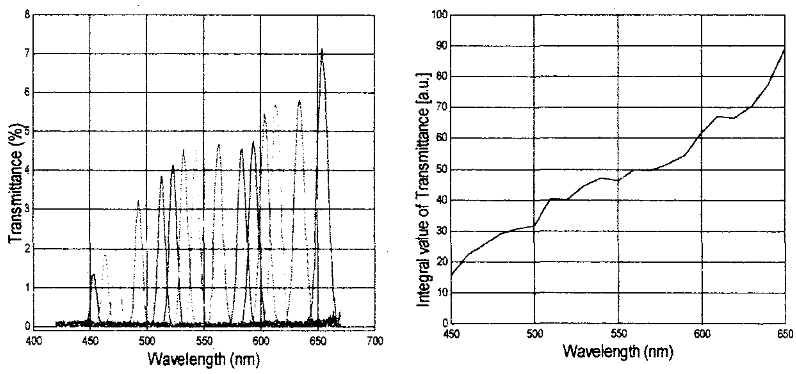
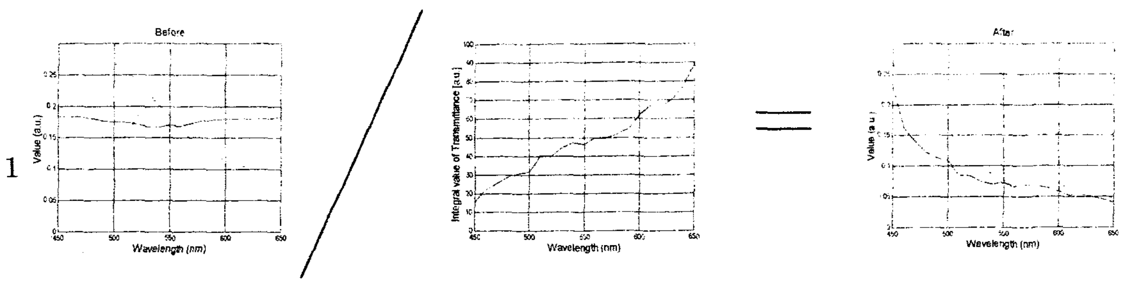


図１９　LCTF の波長透過率特性（左）およびその積分値（右）



(a) Computationally designed filter function　　**(b) Integral value of transmittance of LCTF**　　**(c) Input function to LCTF**

図２０　ＬＣＴＦの制御方法

ることによって、カメラの積分強度は等価的に設計した広帯域フィルタを通過したことと同じ効果を持つことになる。この方法で、４枚の最適化フィルタを実現した結果を図２１に示す。図で、実線はフィルタ関数に光源のスペクトル強度を掛けた分布、点線はLCTFシステムで実現したフィルタの透過関数である。両者のノルム誤差の平均は11.1%であった。

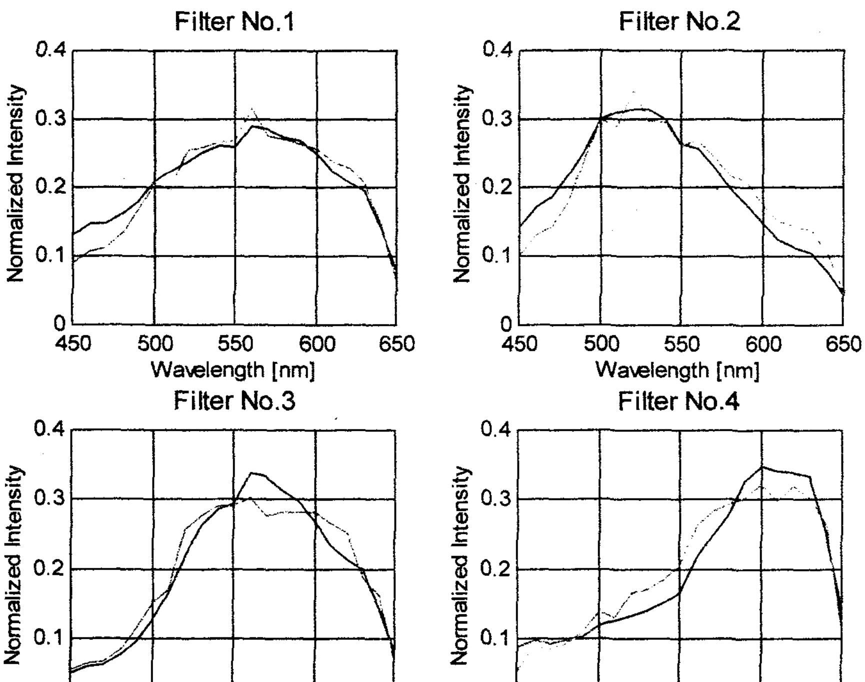


図２１　LCTFシステムによるフィルタの実現結果。
実線：フィルタ関数×光源のスペクトル強度、
点線：LCTFによるフィルタの透過率分布

4. 環境モニタリングへの応用

近年、さまざまな環境汚染が報告される中で、それらが植物に及ぼす被害を把握することの重要性は高まってきている。このような問題に対して、グローバルな観察は、衛星からのリモートセンシングによって定常的に行われている。より身近な植生の環境影響について、分光学的手法による評価についても近年さまざまな角度から研究がなされている。樹葉の分光反射率データに主成分分析を適用し、樹種、季節による変化、大気汚染の影響を詳細に判定できるとの報告もある[20,21]。本研究では植物の葉の分光反射率を測定することに より、その活性状態をモニターすることを試みた[22]。埼玉県南部地域は、夏期にオキシダント濃度が高くなり、光化学スモッグ注意報が出される日がしばしばある。このような大気環境下では、草本類の葉に白斑などの可視被害が現れることが知られている。図２２は、夏期のこのような日常の大気中で育てたハツカダイコンと、オキシダントを浄化するフィルタを通した雰囲気中で育てたハツカダイコンの白斑のない葉の分光反射率を測定した結果である。ごくわずかであるが波長 900nm 付近などに変化が見られる。このようなデータに対して、主成分分析によってストレスの有無の判別を行うことができた。図２３はフォックスグローブアプリコットを約 0.3ppm のオゾンを流した雰囲気中に１時間暴露し、ストレスを与えた後の反射率の経時変化である。近赤外域で激しい吸収帯の変化が見られ、徐々に回復していく様子がわかる。

本研究では、このような対象にたいして、前節までに述べた広帯域分光フィルタシステムを用いた解析を行うまでには至っていないが、今後の課題としたい。

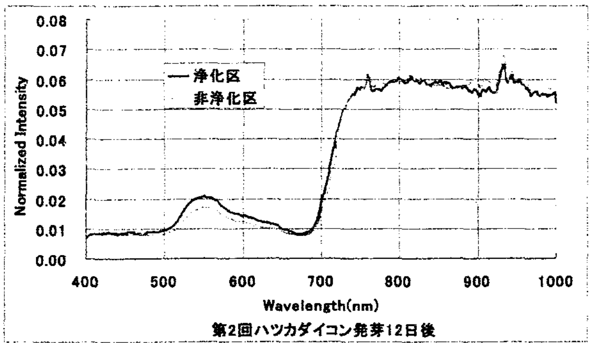


図２１　オゾン浄化および非浄化雰囲気中で生育したハツカダイコンの葉の分光反射率

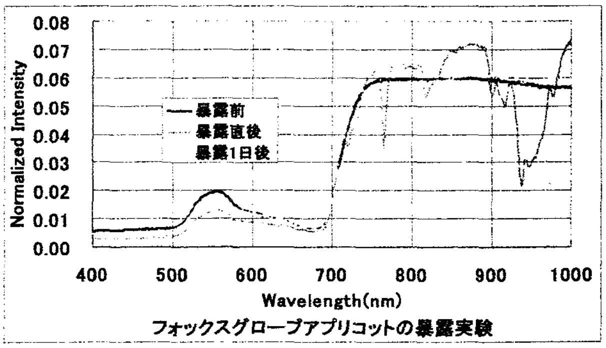


図２２　フォックスグローブアプリコットのオゾン暴露実験、暴露前、暴露直後および暴露後１日の分光反射率変化

5. まとめと今後の課題

本研究は主として可視域におけるカラー画像の理解について、膨大な量の分光画像データを多変量解析法によって解析するだけでなく、ニューラルネットワークによるデータ圧縮法を検討し、それを物理的なフィルタとして実現する方法を提案し、アクティブ型とパッシブ型について、計３種類の広帯域フィルタシステムのプロトタイプを試作した。

（１）アクティブ型スペクトル合成光源

（2） パッシブ型広帯域フィルタシステム

・液晶空間光変調器とリニアバリアブルフィルタを用いたシステム

・液晶チューナブルフィルタを用いたシステム

試作システムにおいては、基本的な性能を示すために、マンセル色標を標準的な色のサンプルとして用いた。すなわち、マンセル色票の分光反射率データベースで学習し、フィルタ関数を決定した。試作システムによって、4枚のフィルタ関数を数%の誤差範囲内でフィルタを実現することができた。このようにして実現したシステムによってカラー物体の観察を行った。システムの評価法として、提案したシステムで撮像された4枚の画像から一般逆行列を用いてスペクトル分布の再生を行い、31枚の狭帯域フィルタを通して計測したスペクトル分布と比較した。色差のよる評価では、ΔEが10を超えるものもあり、スペクトル再生精度については問題が残った。この誤差の原因を考察する。

（1） マンセルデータベースによって作成したフィルタ関数を用いて学習データ以外の対象物を観察したこと。

（2） SOMで最適化したフィルタ関数について、一般逆行列を用いてスペクトル再生を行った。この際、変換行列が特異値近傍にある場合は、大きな誤差を生じるおそれがある。

（3） 試作システムは、液晶素子、偏向板等の光吸収の大きい素子の利用を裂けることができず、画像のSN比を大きくすることができなかった。

これらの問題に対して、今後の検討課題を以下にのべる。

本研究の当初の目的である環境センシングにおいては、観察対象は分光学的に限られた特性を持っているものであり、フィルタ関数を最適化するための学習データは当然観察対象それ自身から採取するべきものである。本研究期間にも、樹葉および草本についてのデータ収集を行ってきており、今後はそれらのデータを学習データとして採用した最適化を行う予定である。

一般逆行列を用いたスペクトル再生には特異値の問題があるが、本研究の本来の目的はスペクトルの再生ではなく、観察対象物の分光学的理解である。その意味では、上記の学習用データベースの選択の問題とあわせて試作システムによる対象物のクラスタリングやパラメータ推定などを今後志向していきたい。また、本研究では最適化手法としてニューラルネットワークの一種であるSOMを用いたが、独立成分分析（ICA）についても今後の検討課題としたい[23]。4節でのべたようなスペクトル分布の変化が特定の原因によるものの場合には有効であると考えられる。

本研究においては、可視域においてのみ議論してきた。これは、実験のしやすさと、従来のこの分野における研究結果との対比が容易であることなどによる。しかし、色画像ではなく、分光画像として取り扱うことのもう一つの利点は、帯域が可視域に限定されないことである。今後の課題であるが、非可視域を含む、計測対象に最も相応しい帯域に、本研究で提案したフィルタ最適化を行うことにより、対象物体に固有の感度特性を有する知的な分光画像認識システムが可能になるであろう。

謝辞

文部省科学研究費補助金の援助のもとに本研究を行うにあたり、ヨエンスー大学（フ

ィンランド）の Parkkinen 教授、Jaaskelainen 教授および彼らのグループとは本研究に関して多くの基調な示唆をいただいたことに対して、感謝の意を表する。また、研究期間にラッペーンランタ工科大学（フィンランド）の Dr.Markku Hauta-Kasari（現在はヨエンスー大学）が文部省奨学生として１年半、フィンランドアカデミーの援助により６ヶ月、計２年間にわたって研究室に滞在し、特に SOM によるフィルタ最適化の問題やアクティブ型システムの構築に多大な協力をいただいた。また、博士後期課程学生であった宮澤佳苗さんには特にパッシブ型の構築に多大な貢献をいただいた。本研究の成果は研究期間中にセンシングシステム研究室に在籍し、本研究にかかわった全ての学生と共有するものであり、ここに謝意を表する。

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Optimal Filters Design for Measuring Colors Using Unsupervised Neural Network

Wenjun WANG, Markku HAUTA-KASARI and Satoru TOYOOKA

In order to measure spectra of colors in an image by a few of filters which have continuous spectral transmittance, an unsupervised neural network is proposed to design non-negative filter functions. The learning algorithm of this neural network is instar algorithm with competition transfer function. Munsell color database is chosen as learning data. Spectra of unknown color were reconstructed by using designed filter functions. Resultant spectral distributions almost coincide with that obtained by a subspace designed by K-L expansion. The average reconstructing error of original colors by using the filter functions is 0.07% and the biggest error is 2.6%. This method was also applied to designing filter functions for estimating optical path difference(OPD) in white light interferometry. The OPD values were successfully estimated.

1. Introduction

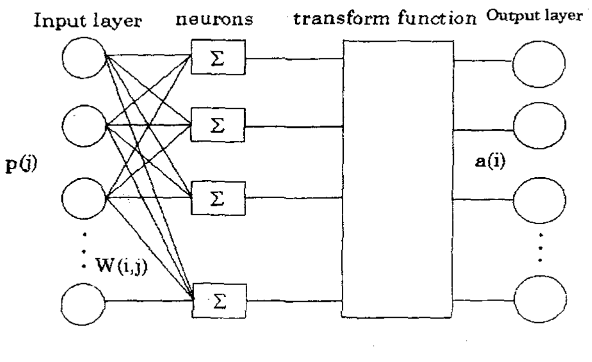
Color image analysis is very important in many fields, such as pattern recognition. Usually three-dimensional color space like CIE XYZ or Lab systems are used to distinguish different colors. Three-dimensional methods are corresponding to human visual system and they can not represent spectral distribution, i.e. sometimes different spectral distributions will result in the same values. The phenomenon is known as metamerism. On the other hand, in some application the spectral distribution is just what we want to analyze. In this case, multi-spectral methods to use a set of narrow band filters are required. If spectral data are sampled in visual wavelength range from 400nm to 700nm with an interval of 10nm, we need 31 filters. Isn't it possible to use fewer filters to find spectral distribution of colors? Subspace method [1]has been successfully used to represent spectral distribution with a few of basis vectors. But because of the orthogonality of the basis vectors, they contain negative values and can not be implemented as real filters. We propose a neural network method to find the optimal filter functions having only non-negative elements. At first we try to make optimal filter functions based on the Munsell color data base[2], because Munsell color base contains almost every color in nature and have very general meaning in the color science. Next we apply the method to measure interference color and to estimate the optical path difference(OPD) in white light interferometry.

2. Design of Neural Network

The idea of designing of filters comes from the subspace method. The filters designed by the neural network will be used as basis vectors. So the filter functions, i.e. basis vectors, should be as independent to each other as possible. Therefore, the set of vectors should satisfy following conditions:

(1) *they should span a subspace including all the color spectra in color data base,*

(2) *these vectors should be separated as long as possible to each other.*



The structure of this neural network is show in Fig.1. The learning data of spectral distributions are fed to the input layer *p(j)* which is connected to neurons inputs through the weight matrix *W(i,j)*. The neurons has a sum that gathers its weighted inputs and send the summation of its weighted *inputs to the transfer function* connected to its output..

Fig.1 Structure of neural network.

The transfer function of this network is competition function which selects its biggest input, i.e. output of neurons as winner and makes its corresponding output 1, while all the other outputs are made 0. The learning algorithm is so-called instar algorithm which was invented by Grossberg[3]. The algorithm can be expressed as following:

$$\begin{aligned} \Delta W_n(i,j) &= r * a(i) * (p(j) - W_n(i,j)) \\ W_{n+1}(i,j) &= W_n(i,j) + \Delta W_n(i,j) \end{aligned} \quad (3)$$

where r is the learning rate which takes value, for example 0.1, $a(i)$ is the output of the network, $W_n(i,j)$ is the weight matrix at the iterative step n. The weight matrix *W(i,j)* is the filter functions we try to design. Munsell color data base is used as learning data which contains 1269 colors, each of them is sampled in the wavelength range from 400nm to 700nm with an interval of 5nm. Then the input layer has 61 units. The output units are 8 since we try to use 8 filters to represent Munsell colors. Figure 2 shows the first 4 filter functions designed by neural network.

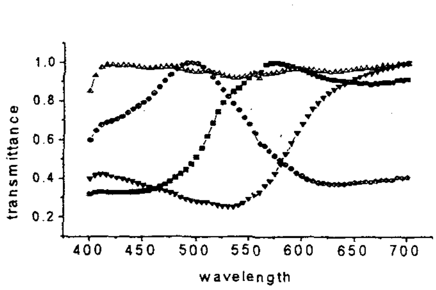


Fig. 2 Filter functions designed.

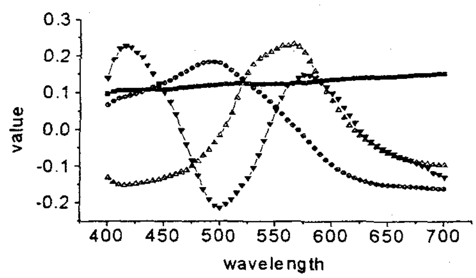


Fig.3 Orthogonalized filter functions.

Figure 3 shows the orthogonalized functions from the filter functions in Fig.2 using Singular Value Decomposition(SVD) algorithm. For comparison other basis vectors were calculated by K-L expansion, which is shown in Fig.4. We find that the basis vectors in Fig.4 are almost similar to the orthogonalized functions in Fig.3 except signs of some vectors are inverted. These results mean that the filters designed by neural network are successfully optimal ones.

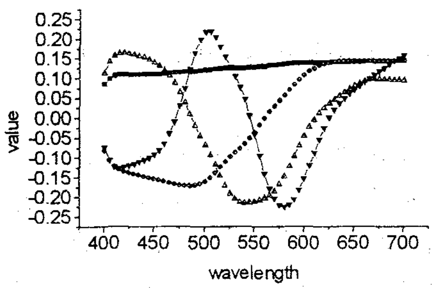


Fig4 Eigenvectors calculated from K-L expansion.

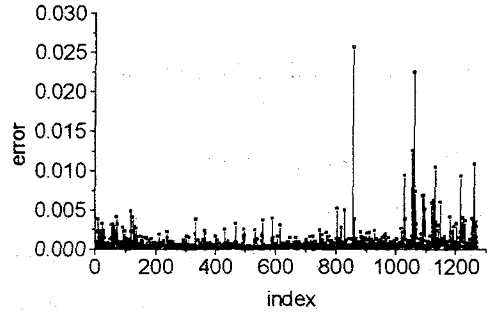


Fig.5 Spectral recovering errors.

Figure 5 shows the recovering error when 8 filters are used to recover the original colors by linear combination of the filters. The average recovering error of original colors is 0.07%. Even the biggest error is less than 2.6%.

3. Application to White Light Interferomeory

In our second experiment, filter functions corresponding to different optical path different(OPD) were designed. The learning database is the set of 101 spectral distribution of interference colors of the OPD values between 0nm to 1000nm. Figure 6 shows the resultant filter functions. The 101 spectral data make a color scale on the subspace spanned by the filter functions as shown in Fig.7.

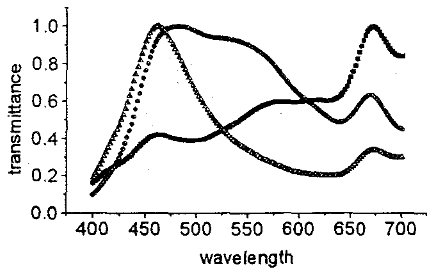


Fig6. Filter functions designed for interference color.

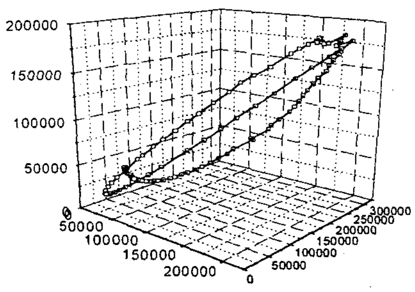
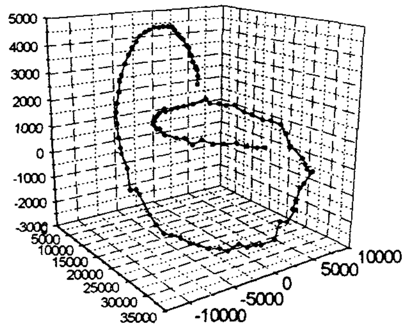


Fig7. Color scale made from filter functions.



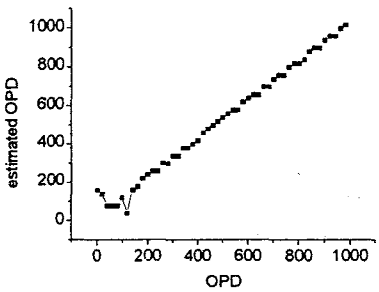


Fig.8 Orthogonalized color scale.

Fig. 9 Estimated OPD.

The unknown interference color is projected on the subspace and an OPD value of the unknown color will be determined on this color scale. But we can see that in Fig.7, some points on scale are very near to each other, almost overlapped, this makes it difficult to decide OPD values correctly. To solve this problem the subspace was linearly transformed to another subspace spanned by orthogonalized set of filter functions. The new color scale is shown in figure8. OPD values of interference colors can be decided on this new color scale. Figure 9 shows the estimated OPD values of a set of test samples. Most of the OPD value were correctly estimated except a few samples of small OPD value.

ACKNOWLEDGEMENT: Wang Wenjun and M.Hauta-Kasari were financially supported by Monbusho. M.Hauta-Kasari was also supported by a grant from Wihuri Foundation. He is on leave from the Dept. of Information Technology, Lappeenranta University of Technology, Finland.

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液晶素子と線形波長可変フィルタを用いた透過型広帯域フィルタ

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LST 22−18

Transparent Broad Band Filters using Liquid Crystal Device and Linear Variable Filter

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Abstract

Spectral distribution of an object color can be represented by a set of inner products between optimized filter functions and the spectral distribution of a sample. In this study, we propose an optical transparent broad-band filter system which can implement arbitrary filter functions. In our system, a test image is observed through the filter part consists of a liquid crystal spatial light modulator (LCSLM) and a linear variable filter (LVF) attached together. The designed filter pattern is written in the LCSLM. The intensity image of a sample is taken while the joint device (LCSLM and LVF) is moving just in front of the lens aperture of the CCD-camera. The spectral distribution of the intensity image through the proposed filter almost coincided with the expected filter functions. From the detected intensity images of the sample, we also reconstructed the spectral image using of generalized inverse matrix.

1. はじめに

我々人間の目は、外界のモノを色と形の情報から認識する。特に色はモノの組成の分光反射率を反映するため、より質的な情報を含んでいるといえる。人間の目はＲＧＢの３値で色を知覚するため情報の欠落が生じる。ところが３値ではなく分光反射率として情報をとらえれば、１つの色に対して分光反射率は１つに決まり、かつ測定対象に応じて観測波長域を広げることが出来る。本研究では人間の目では判別不可能な、モノの分光反射率の微妙な違いから、それを識別・分類することを目的としている。特にそれを画像として取り扱うこと、また実験室内に限らず屋外でも測定可能であること、データ量をなるべく小さくすることを目標としている。

モノの分光反射率は、数枚のフィルタ関数で展開できる。言い換えれば数枚のフィルタ関数とモノとの間の内積値が求まれば、元の分光反射率が再構築できる。これまでに、主成分分析によって上位の基底関数に対応するフィルタ関数を求め、それを通して撮像した数枚の画像から、部分空間

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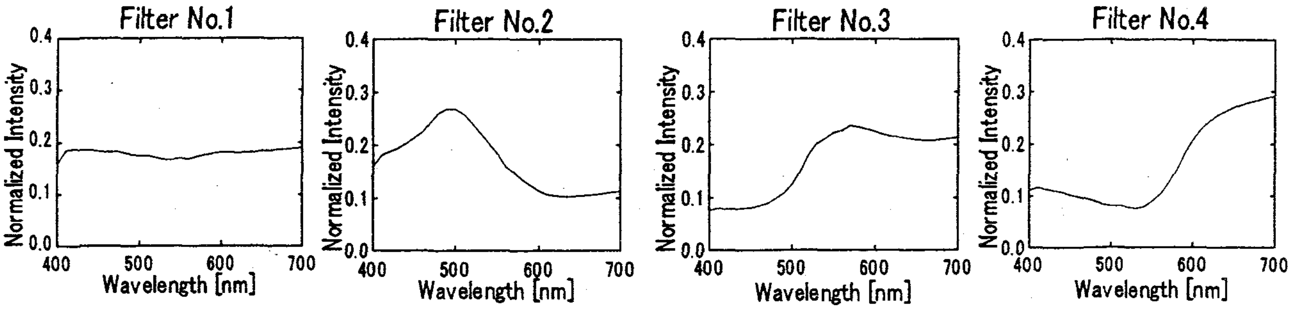

Figure 1　Designed filter functions

法[1]によりモノの識別・分類あるいは分光反射率の再構築が行われた[2)3)]。しかし部分空間法で求めたフィルタ関数は、互いに直交する性質を持つため必ず負の値を含む。そのためフィルタ関数を直接光学系に導入することが困難であった。Hauta-Kasari ら[4]は、教師無しニューラルネットワークを用いることにより、負の値を持たないフィルタ関数を設計した。これによりフィルタ関数を直接光学系に組み込むことが容易となった。

フィルタ関数とモノとの間の内積値を求める方法は、２つ考えられる。第１の方法は、フィルタ関数に相当するフィルタを物理的に作製し、それを通してモノを撮像することである。しかし本研究で用いるフィルタ関数は対象に応じて設計するため、それに応じて透過率分布を任意に変化させる必要がある。しかしそのようなフィルタを物理的に作製することは難しい。そのため第１の方法を実現することは困難であると考えられてきた。第２の方法は、フィルタ関数に相当する波長分布を持つ光を作製し、その光に照射されたモノを撮像することである[3) 5)]。この方法は実験室内では有効であるが、作製した光源をモノに照射しなければならないという制限から、屋外での測定には不向きである。

そこで本研究では、任意の光源で照射されたモノの測定を可能にする第一の方法の実現を試みた。ここでキーデバイスとなるのが液晶素子と線形波長可変フィルタである。特に線形波長可変フィルタが、本方法の実現に大きく寄与したと言える。

2.　最適化フィルタ

2.1　最適化フィルタの設計

本研究では、対象物体に応じてフィルタを設計する。フィルタの設計方法として、教師無しニューラルネットワークを用いた[4]。今回は、１２６９色のマンセルカラーチップ[6]の分光反射率をデータベースとして、それをもとに最適化フィルタを設計した。フィルタの数はニューラルネットワークの性質上、何枚にでも設定できるため、ここでは例として４枚に設計した（Fig. 1）。この４つのフィルタ関数を用いれば、少なくとも全てのマンセルカラーの分光反射率を再構築できることを意味している。もっと一般化して言うならば、マンセルカラーチップが自然界のあらゆる色を網羅したデータベースであると仮定すれば、この４つのフィルタ関数から自然界のあらゆる色が再構築できるということになる[5]。そこで本研究で提案するシステムの有用性を確かめるため、まず４つのフィルタの物理的作製を行い、次に４つのフィルタを通して撮像した４枚の白黒画像から、元の分光反射率を再構築することを試みた。

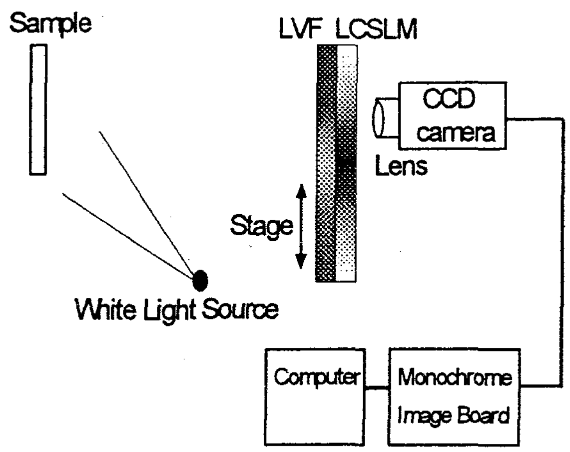

Figure 2　Experimental setup

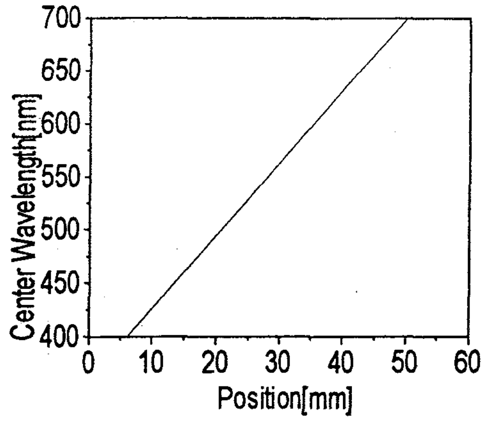

Figure 3　Characteristics of the Linear Variable Filter

2.2 最適化フィルタによる分光反射率の再構築

教師無しニューラルネットワークで求めたフィルタ関数は、部分空間法で求めたそれとは異なり直交化しないため、元の分光反射率Sを再構築するには一般化逆行列を用いる必要がある。

$$S' = W(W^TW)^{-1}W^T S \qquad (1)$$

ここでWはフィルタ関数である。$W(W^TW)^{-1}$ は既知の値、$W^T S$ はフィルタと被測定物体の分光反射率との内積値であり実験から得られる値なので、再構築した分光反射率S'が求まる。

3. 実験

3.1 透過型広帯域フィルタシステム

Figure 2に実験装置を示す。本装置のフィルタ部は、液晶空間光変調素子（ＬＣＳＬＭ）と線形波長可変フィルタ（ＬＶＦ）から構成されている。ＬＶＦはサイズが６０×２０×５t[mm] の干渉フィルタであり、長軸方向の位置に対応して透過波長が４００～７００[nm]まで線形に変化するものである（Fig. 3）。ＬＣＳＬＭには最適化されたフィルタ関数に応じた濃淡パターンを２５６階調で書き込む。ＬＣＳＬＭとＬＶＦは互いに密着させ、ＬＶＦの長軸方向が１軸移動ステージの移動方向と一致するようにステージ上に取り付ける。被測定物体の強度画像は、フィルタ部（ＬＣＳＬＭとＬＶＦ）を通して白黒ＣＣＤカメラで撮像される。ＣＣＤカメラのシャッターは、フィルタ部が移動ステージによってＣＣＤカメラのレンズ開口前をちょうど横切る間、開かれている。したがって撮像された強度画像は、フィルタ部がＣＣＤカメラ前を横切っている間の積分画像となる。

3.2 作製フィルタの検証

本装置により撮像した強度画像が、望むフィルタを通した画像になっているか確かめる実験を行った。Figure ２に示される被測定物体には標準白色版（ＢａＳＯ4）を用い、ハロゲンランプで照射した。ＬＣＳＬＭに書き込む濃淡パターンを固定したままで、ＣＣＤカメラのレンズ直前に４００～７００[nm]まで１０[nm]おきに３１枚の狭帯域干渉フィルタを挿入し、移動ステージをそのつど動かし、３１枚の強度画像を

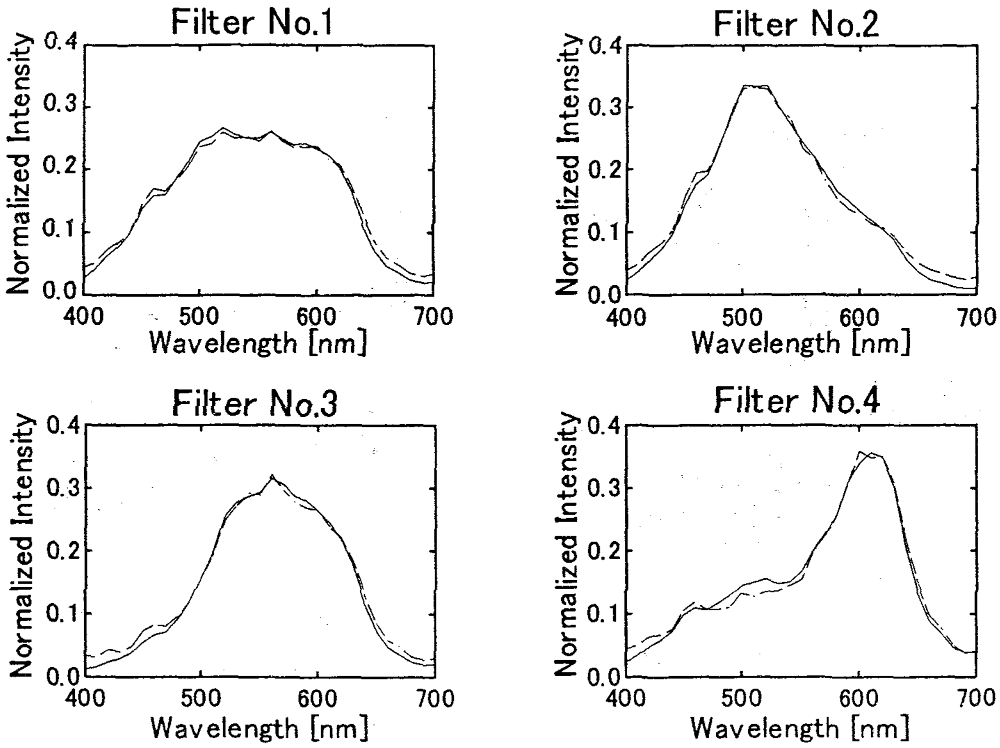

Figure 4 Experimental results. Solid lines are expected filter functions and dashed lines are optically implemented filters.

取り込んだ。１枚の強度画像につき１０×１０ピクセルのウィンドウ内で平均強度を計算し、分光反射率分布を求めた。ここでは４つのフィルタ関数に対して４種類の濃淡パターンをＬＣＳＬＭに順次書き込み、それぞれについて分光反射率分布を求めた。Figure 4に結果を示す。実線は、Fig. 1で示した望むフィルタ関数に光源の波長分布をかけ合わせたもの、破線は実験で測定したフィルタの分光反射率分布である。どのフィルタもよく一致しており、最大誤差は6．4％、平均誤差は5．8％であった。

3. 3 分光反射率の再構築

マンセルカラーチップをデータベースとして作製したこの４つのフィルタ関数から自然界のあらゆる色が再構築できると仮定し、マンセルカラーチップには無い、赤、黄、緑、青の計４枚のカラーシートを被測定物体として使用した。Figure 4に示す４枚のフィルタを通して、カラーシートの強度画像をＣＣＤカメラで取り込んだ。得られた４枚の強度画像から、（１）式に示す一般化逆行列を用いて、画像のピクセルごとの分光反射率を再構築した。比較のため、４００～７００[nm]まで１０[nm]おきに３１枚の狭帯域干渉フィルタをＣＣＤカメラのレンズ直前に入れ、３１枚の強度画像を取り込み、分光反射率を求めた。Figure 5に結果を示す。実線は３１枚の狭帯域干渉フィルタで測定した分光反射率、破線は本システムを用いて求めた４枚の強度画像から再構築した分光反射率である。カラーシートの映っている場所の中から代表的なピクセル４点を選んで表示した。左から赤、黄、緑、青の結果である。まだ誤差は大きいが、大まかな色味は再現されている。

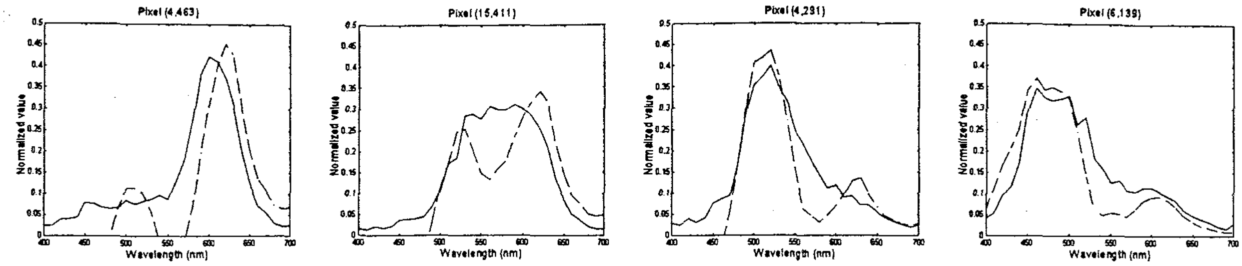

Figure 5 The Spectra at four different locations of the spectral image. Solid lines correspond to the spectral image measured by the CCD-camera with 31 narrow band interference filters and dashed lines correspond to the spectral image measured by the transparent broad band filter system using 4 filters.

4. まとめ

教師無しニューラルネットワークを用い、１２６９色のマンセルカラーチップの分光反射率をデータベースに設計した４枚の最適化フィルタの光学的実現を行った。液晶空間光変調素子と線形波長可変フィルタをキーデバイスとして用いた、透過型広帯域フィルタシステムを提案した。本システムにより４枚の最適化フィルタを物理的に作製した結果、その誤差は６％程度に抑えられた。これより、任意の波長透過率分布をもつ透過型広帯域フィルタが実現できることが示された。また液晶空間光変調素子への濃淡パターンを書き換えることにより、異なる波長透過率分布を持つフィルタを順次作製することができた。

本システムの有用性を確かめるため、４枚の最適化フィルタを通して撮像した４枚の強度画像から、もとの分光反射率の再構築を試みた。その結果、誤差は大きいが大まかな色味は再現された。今回はフィルタの数を４枚に設定したが、フィルタの枚数を最適化することで、精度が向上するものと予想される。本手法で扱うデータ量は、３１枚の狭帯域干渉フィルタを通して画像を得る方法と比較すれば、単純計算して８分の１程度であり、少ないデータ量から望む情報が得られることが利点である。また、今回は実験室内で試験的に計測を行ったが、本システムは光源を選ばないため、屋外での計測も考えられる。

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Spectral Vision System for Color Image Analysis

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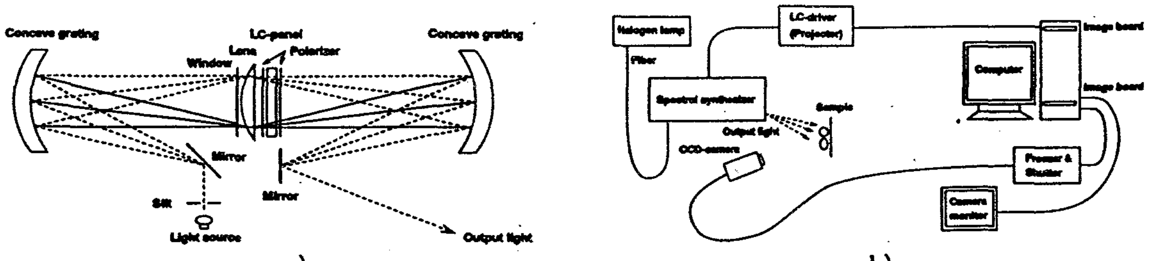
Abstract. In this study we present a spectral vision system, which can be used to acquire a color spectrum and two-dimensional spectral images. First we designed a low-dimensional color filter set by the unsupervised neural network. Then we constructed a compact size optical setup for the spectral synthesizer, which synthesizes the light corresponding to the spectral characteristics of the color filter. The sample was illuminated by the synthesized lights and the intensity images, which correspond to the inner products between the color filter set and the sample's spectra were detected by the CCD-camera. From the detected inner products the sample's color spectra were reconstructed by the use of generalized inverse matrix. The experimental results of acquiring a single color spectrum and natural spectral images are presented.

1. Introduction

Multispectral imaging has received a great deal of attention recently. Spectral measurements are used for example in the field of remote sensing, computer vision and industrial applications. Due to the high accuracy of the spectral information, it has become an important quality factor in many industrial processes. When the multispectral imaging system measures the visible light, then the measured image represents a high quality color image, where every pixel contains a color spectrum. In this paper we propose a spectral vision system to acquire color spectra and two-dimensional spectral images.

2. Spectral Vision System

In our previous study [1] we designed a low-dimensional color filter set by the unsupervised neural network for the color spectra database measured from the *Munsell Book of Color*. Designed color filters are used in our spectral vision system, where the sample is illuminated by the light, which has the spectral characteristics of the designed color filter. To synthesize the light, we constructed a optical setup for the spectral synthesizer shown in Fig. 1 a). The color filters were implemented optically by the use of liquid crystal (LC) spatial light modulator [2]. The experimental setup for the spectral vision system is shown in Fig. 1 b). A sample is illuminated by the synthesized lights and the intensity images corresponding to the inner products between the color filter and the sample are detected by the CCD-camera. Sample's color spectrum s' is then reconstructed by the use of generalized inverse matrix $s' = W(W^TW)^{-1}W^Ts$, where W is the filter set and W^Ts contains optically calculated inner products.

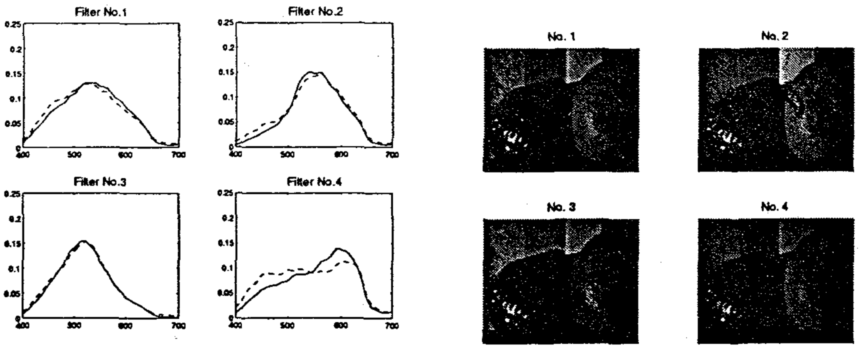


a) b)

Figure 1: a) Optical setup for the spectral synthesizer. b) Experimental setup for the spectral vision system.

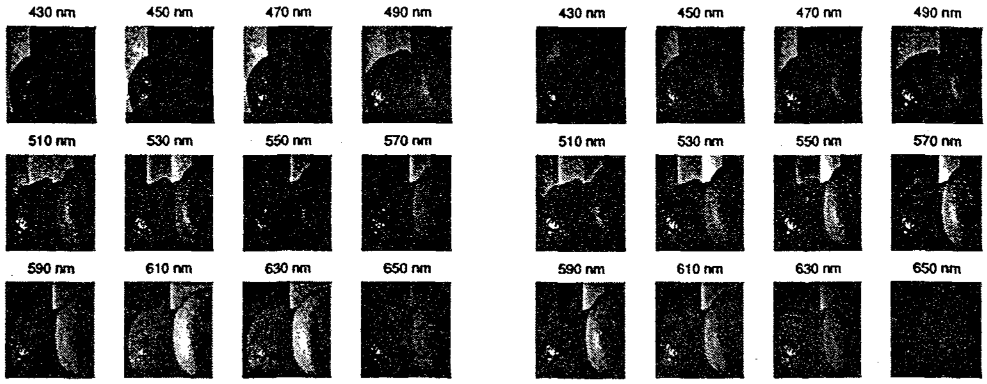
3. Experiments

We investigated the optimal dimension for the filter set experimentally. The samples were transparent color slides made from Munsell color chips and we acquired the spectra by the filter sets of 3,4,5 and 6 filters. In the series of experiments using different number of filters, four filters gave best results, which was selected as the dimension of our model. Next we acquired a two-dimensional spectral image. A real world object was a set-up of a strawberry and an orange lying in the front of a colored panel. The sample was illuminated by four filters shown in Fig. 2 a) and the intensity images shown in Fig. 2 b) were detected by the CCD-camera. From the intensity images the spectral image was reconstructed by the use of generalized inverse matrix. To compare the results, we measured the same image by the use of CCD-camera with 31 narrow band interference filters. Fig. 3 shows the results at the wavelength range from 430nm to 650nm at 20nm intervals.



a) b)

Figure 2: a) Filter set of 4 filters. Solid lines are designed filters and dashed lines are optically implemented filters. b) Detected intensity images from the filtering process.



a) b)

Figure 3: a) Spectral image acquired by our spectral vision system using 4 filters. b) Spectral image measured by the use of CCD-camera with 31 narrow band interference filters.

4. Conclusions

Our spectral vision system can be used to acquire a single color spectrum and two-dimensional spectral images. The data obtained by our method is small and therefore convenient for storing and transmitting spectral images. The optical system is used to calculate the optical inner product, and therefore this system can be used in various optical pattern recognition tasks, in which the algorithm contains the inner product calculation.

Acknowledgements

This work was done when Markku Hauta-Kasari was visiting researcher at the Graduate School of Science and Engineering, Saitama University, Japan. He was supported by the scholarships from the Japanese Ministry of Education and from the Lappeenranta University of Technology, Finland. This work was also partly supported by the Grant-in-Aid for Development Scientific Research (B) (No. 10555013) of the Japanese Ministry of Education.

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Optical Implementation of Transparent Broad-Band Filters for Spectral Image Analysis

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Abstract. Spectral distribution of an object color can be represented by a set of inner products between optimized filter functions and the spectral distribution of a sample. In this study, we propose an optical transparent broad-band filter system which can implement arbitrary filter functions. In our system, a test image is observed through the filter part consists of a liquid crystal spatial light modulator (LCSLM) and a linear variable filter (LVF) attached together. The designed filter pattern is written in the LCSLM. The intensity image of a sample is taken while the joint device (LCSLM and LVF) is moving just in front of the lens aperture of the CCD-camera. The spectral distribution of the intensity image through the proposed filter almost coincided with the expected filter functions.

1. Introduction

Spectral based analysis of color is important in many fields such as computer vision and inspection of industrial products. Spectral distribution of an object color can be expanded by a set of filter functions designed by the unsupervised neural network[1], so it can be represented by a set of inner products between the spectral distribution of a sample and the color filters corresponding to the filter functions. In our previous method[2], the inner products were obtained by taking intensity images of a sample illuminated by the synthesized lights corresponding to the spectral characteristics of the optimized color filters. But it is difficult to apply for measuring the samples illuminated by an arbitrary light source like the sun. In this paper, we propose a new system to implement optical transparent broad-band filters which can be renewed arbitrarily.

2. Optical Transparent Broad-Band Filter System

An experimental setup for a proposed transparent broad-band filter system is shown in Fig.1. The filter part of this system consists of a liquid crystal spatial light modulator (LCSLM) and a linear variable filter (LVF). Both components are attached each other and mounted on a linear stage. The transmitting wavelength of the LVF is linearly varied depending on the position parallel to the moving direction of the stage. The designed filter patterns corresponding to the optimized color filters are written on the LCSLM. The intensity image of a sample is taken by a CCD-camera through the joint device (LCSLM and LVF).

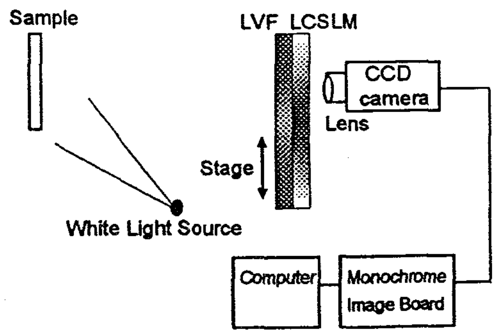

Fig.1 Experimental setup

The shutter of the CCD-camera is opened for a period while the joint device is moving just in front of the lens aperture of the CCD-camera.

3. Experiments

To investigate the validity of this system, the intensity images for the spectral distribution were measured through 31 narrow band interference filters from 400nm to 700nm at 10nm intervals. In experiments, a standard white board of $BaSO_4$ illuminated by a halogen lamp was observed through the proposed filter system. Four filter functions[1] were used as the optimized color filters. The average intensity inside the window of 10×10 pixels was calculated to obtain the spectral distribution. Figure 2 shows the experimental results. Solid lines are expected filter functions which is the product between the optimized four filter functions and a light source spectrum, and dashed lines are the spectral distributions of the optically implemented filters. Both distributions almost coincide. The maximum error is 8.1% and average error is 5.7%.

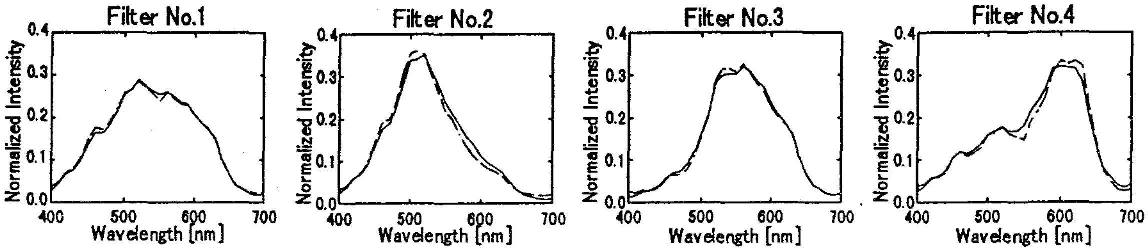

Fig.2 Experimental results. Solid lines are expected filter functions and dashed lines are optically implemented filters.

4. Conclusions

We proposed the optical transparent broad-band filters, in which the transmittance can be changed arbitrarily. The spectral distribution of the intensity image through the proposed filter almost coincided with the expected filter functions. This system can be used for two-dimensional spectral image analysis under arbitrary illuminating conditions.

Acknowledgements

This study is supported by the Grant-in-Aid for Developmental Scientific Research (B) (No.10555013) of the Japanese Ministry of Education, Science, and Culture.

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Rewritable broad-band filters for color image analysis

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ABSTRACT

In this study, we propose an optical transparent broad-band filter system which can be used to measure a color spectrum and two-dimensional spectral images. The filter function of this system can be changed and rewritten arbitrarily. Spectral distribution of an object color can be represented by a set of inner products between optimized filter functions and the spectral distribution of a sample. In our system, a test image is observed through the filter part consists of a liquid crystal spatial light modulator (LCSLM) and a linear variable filter (LVF) attached together. The intensity image of a sample is taken while the joint device (LCSLM and LVF) is moving just in front of the lens aperture of the CCD-camera. The spectral distribution of the intensity image through the proposed filter almost coincided with the expected filter functions. From the detected intensity images correspond to the inner products between the color filters and a sample, the color spectra of the sample were reconstructed by the use of inverse matrix. The data obtained from the filtering process is only four monochrome images. It is convenient for storing and transmitting the spectral image. The experimental results of measuring a color spectrum and two-dimensional spectral images are presented.

Keywords: Broad-band filter, color, color filter, color spectra, spectral image, linear variable filter (LVF), liquid crystal spatial light modulator (LCSLM).

1. INTRODUCTION

Spectral based analysis of color is important in many fields such as machine vision and inspection of industrial products. Spectral distribution of an object color can be expanded by a set of filter functions, so it can be represented by a set of inner products between the spectral distribution of a sample and the color filters corresponding to the filter functions. Subspace method[1] which is based on KL-expansion has been successfully used to represent the spectral distribution with a few of basis vectors.[2,3] However, due to the orthogonality of the eigenvectors, the corresponding color filters usually contain negative coefficients and cannot be implemented in optical components directly.

Hauta-Kasari et al.[4] proposed design of a low-dimensional color filter set which is contain only positive coefficient by the unsupervised neural network. The positive color filters span the color space very similar to the color space spanned by the eigenvectors of the subspace method. The color filters with positive coefficients can be directly used in optical implementations.

There are two ways to obtain inner products between the spectral distribution of a sample and the color filters corresponding to the filter functions. One approach is to take intensity images of a sample illuminated by the synthesized lights corresponding to the spectral characteristics of the optimized color filters.[2,3,5] This method is useful for indoor measurement, but it is difficult to apply for measuring samples illuminated by an arbitrary light source like the sun. This problem can be overcome by another method i.e. taking intensity images of a sample through the color filters.

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SPIE Vol. 3740 • 0277-786X/99/$10.00

In this paper, we propose a new system to implement optical transparent broad-band filters whose transmittance can be changed and rewritten arbitrarily. We applied this system to acquire a color spectrum and two-dimensional spectral images.

2. OPTIMIZED COLOR FILTERS

In this study, we used the optimized color filter set with positive coefficients designed by the unsupervised neural network[4] for the 1269 Munsell[6] spectra. The color filters are used to reconstruct the spectrum. Figure 1 shows the four filter functions used as the optimized color filters in this study.

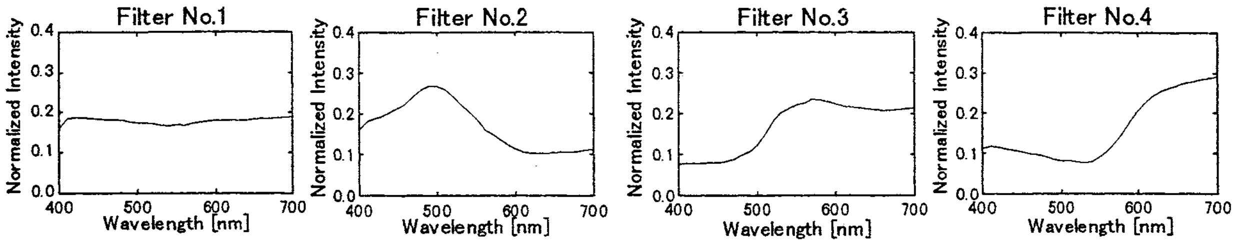

Figure 1. Designed filter functions

Because of the designed filter set is non-orthogonal, the reconstructed spectrum s' is obtained by the inverse matrix:

$$s' = W(W^TW)^{-1}W^Ts\,, \tag{1}$$

where W is the filter set. In the optical implementation, the inner products W^Ts between the filter set W and the sample's spectrum s can be determined optically and $W(W^TW)^{-1}$ is known.

3. EXPERIMENTS AND RESULTS

3.1 Broad-band filter system

An experimental setup for a proposed transparent broad-band filter system is shown in Fig.2. The filter part of this system consists of a liquid crystal spatial light modulator (LCSLM) and a linear variable filter (LVF). The LVF is a kind of interference filter whose wavelength range is from 400nm to 700nm. Figure 3 shows the relationship between the transmitting center wavelength of the LVF and its position. The transmitting wavelength of the LVF is linearly varied depending on the position parallel to the moving direction of the stage. The designed filter patterns corresponding to the optimized color filters are written on the LCSLM. Both components are attached each other and mounted on a linear stage. The intensity image of a sample is taken by a CCD-camera through the joint device (LCSLM and LVF). The shutter of the CCD-camera is opened for a period while the joint device is moving just in front of the lens aperture of the CCD-camera. In this system, we can make any color filters only by changing the input pattern on the LCSLM.

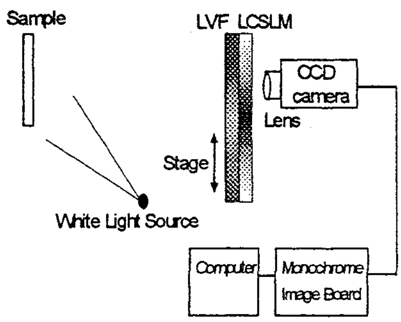

Figure 2. Experimental setup

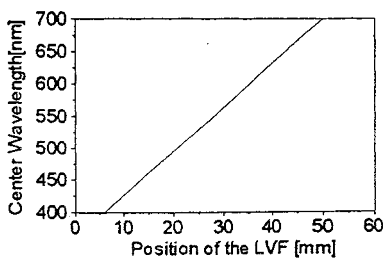

Figure 3. Characteristics of the Linear Variable Filter

To investigate the validity of this system, the intensity images for the spectral distribution were measured through 31 narrow band interference filters from 400nm to 700nm at 10nm intervals. In this experiments, a standard white board of BaSO4 illuminated by a halogen lamp was observed through the proposed filter system. The average intensity inside the window of 10 × 10 pixels was calculated to obtain the spectral distribution. Figure 4 shows the experimental results. Solid lines are the expected filter functions which is the product between the optimized four filter functions and a light source spectrum, and dashed lines are the spectral distributions of the optically implemented filters. Both distributions almost coincide within average error of 5.4%.

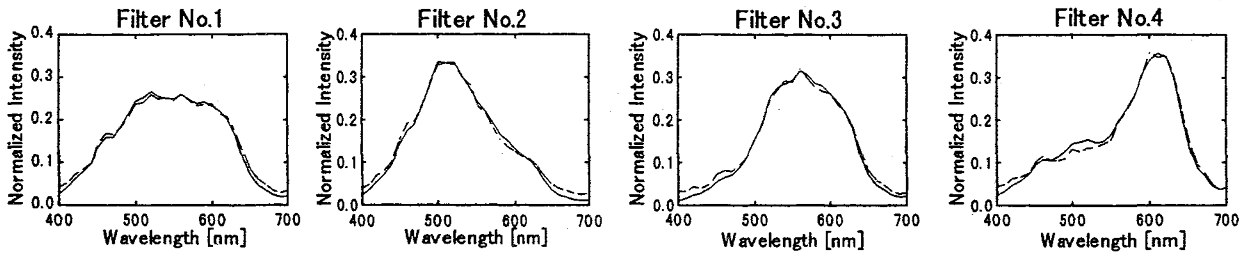

Figure 4. Experimental results. Solid lines are the expected filter functions and dashed lines are the optically implemented filters.

3.2 Spectrum reconstruction

We applied this system to acquire the spectral image of a real world object. A strawberry, a kamquat (a fruit like an orange) and four color sheets (Blue, Green, Yellow, Red) were used as the tested samples in the one image. From the detected intensity images of the sample through the proposed four filters shown in Fig.4, we reconstructed the spectral image by the use of inverse matrix in Eq.(1). To compare the results, we measured the same spectral image by the CCD-camera with 31 narrow band interference filters. Figure 5 shows the reconstructed spectra at the different locations of the spectral image. The spectra at the upper part of the figure are from left to right: painted blue color sheet, painted green color sheet and glossy yellow color sheet. The spectra at the lower part of the figure are from left to right: glossy red color sheet, strawberry and kamquat.

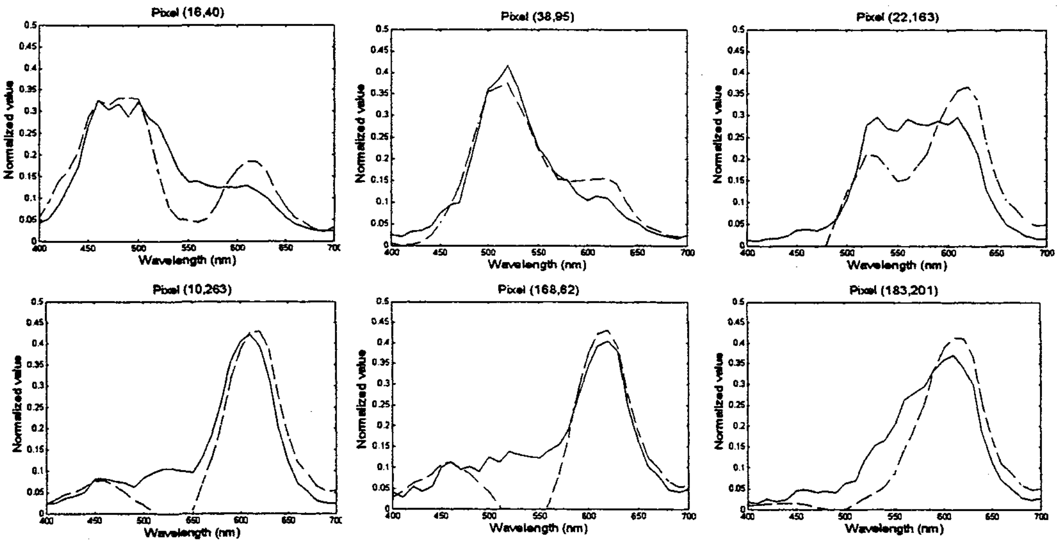

Figure 5. The spectra at the different locations of the spectral image. Solid lines are the measured spectra with 31 narrow band filters, and dashed lines are the reconstructed spectra from 4 intensity images.

4. CONCLUSIONS

We proposed the optical transparent broad-band filter system which can be used to measure a color spectrum and two-dimensional spectral images. The transmittance of the filter function could be changed and rewritten arbitrarily only by changing the input pattern on the LCSLM. The spectral distribution of the intensity image through the proposed filter almost coincided with the expected filter functions. From the detected intensity images, we acquired the color spectra of a sample by the use of inverse matrix. This acquired spectra were compared to the spectra measured by the CCD-camera with 31 narrow band filters. The spectra obtained by the both method correlated well. The data obtained from the filtering process is only four monochrome images. It is convenient for storing and transmitting the spectral image. This system can be used under arbitrary illuminating conditions.

ACKNOWLEDGMENTS

This study is supported by the Grant-in-Aid for Developmental Scientific Research (B) (No.10555013) of the Japanese Ministry of Education. This study is also supported by the Toyota High-tech Research Grant Program. The Munsell spectra database is available at the www-server of the Lappeenranta University of Technology, Finland, http://www.it.lut.fi/research/color/lutcs_database.html.

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Spectral measurements of two-dimensional color images

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ABSTRACT

In this work we propose a prototype of the spectral vision system, which can be used to measure a color spectrum and two-dimensional spectral images. We first designed a low-dimensional broad band color filter set with a constraint of positive spectral values by the unsupervised neural network. Then we constructed a compact size optical setup for the spectral synthesizer, which can be used to synthesize the light corresponding to the spectral characteristics of the color filter. In the optical setup we implemented the color filters by the use of the liquid crystal spatial light modulator (LCSLM). In our experiments we illuminated a sample of a real world scene by the synthesized lights and detected the intensity images of the filtering process by the CCD-camera. The intensity images correspond to the optically calculated inner products between the color filters and a sample. The data obtained from the filtering process is only a few monochrome images and therefore convenient for storing and transmitting spectral images. From the detected inner products we reconstructed the sample's color spectra by the use of inverse matrix. We present experimental results of measuring a single color spectrum and two-dimensional spectral images.

Keywords: Spectral image, spectral imaging, color, color filter, color spectra, optical pattern recognition

1. INTRODUCTION

The use of spectral imaging in industrial machine vision applications has received a great deal of attention recently. Since the first prototype for the multispectral imaging instrument proposed in the beginning of 1970's, the spectral imaging has been mainly used in the field of remote sensing. However, due to the recent technological development in optics and computers, the spectral imaging is becoming an important tool in the quality control of industrial products. Currently in industrial use there are two basic approaches to measure two-dimensional spectral images. One approach is based on the acquisition of a two-dimensional image at different wavelengths at different times, for example by the use of a CCD-camera with a set of narrow band interference filters, which are placed on a rotating filter wheel.[1] Another approach is based on the acquisition of line images with a simultaneous measurement of spectra at different wavelengths by scanning the camera or an object along the spatial axis.[2]

From the spectral measurements a large amount of data has to be stored or transmitted. One approach to compress spectra is to have the measured spectra and compress them by software.[3–5] Another approach is to design the low-dimensional multispectral imaging system so that we already acquire the optimal component images for spectral reconstruction.[6,7]

In this paper we propose a low-dimensional multispectral imaging system, which can be used to measure a color spectrum and two-dimensional spectral color images. The proposed method is fast and the data obtained from the filtering process is small, and therefore convenient for storing and transmitting a spectral image.

The paper is organized as follows. In Section 2 we briefly review the color filter design from our previous study. Then in Section 3 we introduce the optical setup for the spectral synthesizer and the experimental setup for the spectral vision system. Finally in Section 4 we show the experimental results of our measurements and in Section 5 we give a discussion.

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SPIE Vol. 3740 • 0277-786X/99/$10.00

2. COLOR FILTERS

In our previous study (see Ref. 8) we designed a low-dimensional color filter set with a constraint of positive spectral values by the unsupervised neural network for the 1269 Munsell[9] spectra. The competitive learning algorithm was based on the Instar-algorithm by Grossberg,[10] which was incorporated by Kohonen's[11] self-organizing map (SOM) with the winner take all (WTA) layer. The neural network clusters the color spectra, and after learning the centers of the clusters are used as color filters. The detailed description of the competitive learning and self-organization can be found in Refs. 10–12. In Ref. 8 we showed that the Munsell spectral database was reconstructed with a sufficient accuracy by the designed color filters and the reconstruction accuracy was comparable to the Karhunen-Loève transform based subspace method. Fig. 1 shows the filter set of 4 filters used in this study.

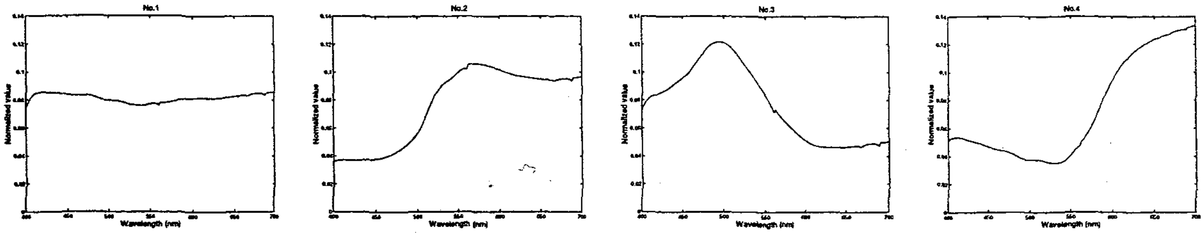


Figure 1. Filter set of 4 learned filters used in proposed spectral vision system.

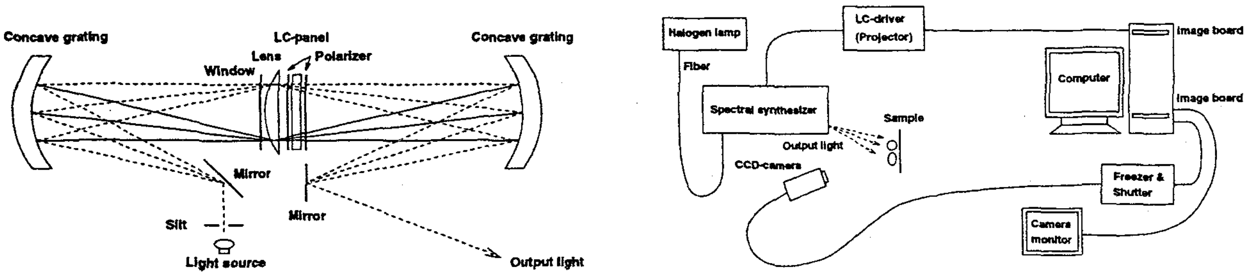
Designed color filter set is non-orthogonal and to use it to reconstruct a spectrum s, an inverse matrix can be used:

$$s' = W(W^TW)^{-1}W^Ts, \tag{1}$$

where W is the filter set. In the optical implementation $W(W^TW)^{-1}$ is known and the inner products W^Ts between the filter set W and the sample's spectrum s are determined experimentally. The filter effect on the sample can be produced either by filtering a reflecting or transmitting light of the sample[13] or by illuminating the sample by the synthesized light, which has the spectral characteristics of the color filter.

3. SPECTRAL VISION SYSTEM

The inner products W^Ts in Eq. (1) between a broad band color filter set W and a sample s can be calculated optically by the use of the liquid crystal panel.[6,14] If the sample is illuminated by the synthesized light, which has *the spectral characteristics of the color filter W_i, then the detected intensity of the sample corresponds to the inner* product W_i^Ts. To synthesize the light corresponding to the color filter, we constructed the optical setup shown in Fig. 2 a). The experimental setup for the spectral vision system is shown in Fig. 2 b).



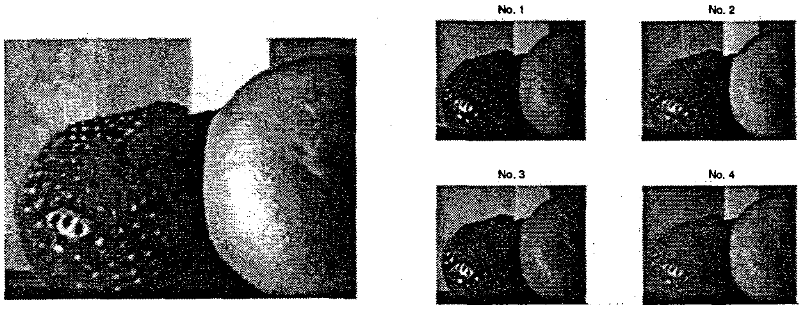
a) b)

Figure 2. a) Optical setup for the spectral synthesizer. b) Spectral vision system.

4. EXPERIMENTS

We acquired the spectral image from a real world object by our spectral vision system. As a real world scene shown in Fig. 3 a) we used a setup of a strawberry and a mandarin lying on a table in front of a colored panel. We illuminated the sample by 4 synthesized lights corresponding to the color filters shown in Fig. 1 and the reflected intensity images shown in Fig. 3 b) were detected by the CCD-camera.

From the detected intensity images we reconstructed the spectral image in the wavelength range from 400nm to 700nm at 10nm intervals by the use of inverse matrix in Eq. (1). To compare the results, we measured the same spectral image by the CCD-camera with 31 narrow band interference filters covering the wavelength range from 400nm to 700nm, at 10nm intervals. Fig. 4 shows examples of the spectra at the different locations of the spectral image. The spectra at the upper part of the figure are from left to right: painted blue color sheet, painted green color sheet and glossy yellow color sheet. The spectra at the lower part of the figure are from left to right: glossy red color sheet, strawberry and mandarin.



a) b)

Figure 3. a) Sample as a gray level image, illuminated by the halogen lamp. b) Detected intensity images of the sample, illuminated by the synthesized lights, which correspond to the 4 color filters.

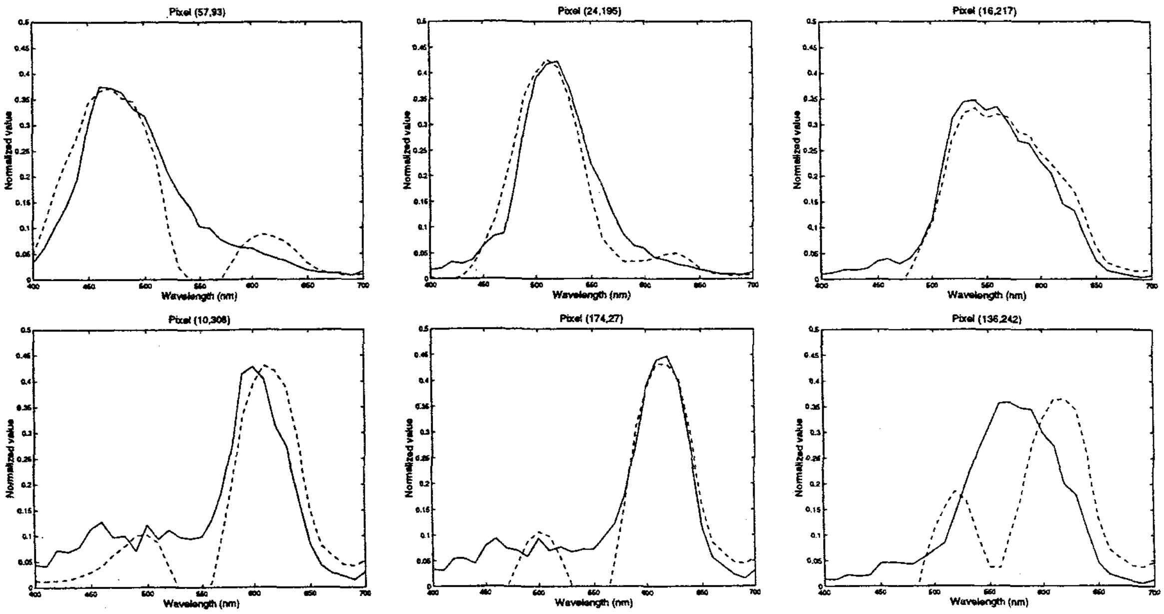


Figure 4. The spectra at six different locations of the spectral image. Solid lines correspond to the spectral image measured by the CCD-camera with 31 narrow band filters and dashed lines correspond to the spectral image measured by the spectral vision system using 4 filters.

5. DISCUSSION

We presented a prototype of the spectral vision system, which can be used to measure a color spectrum and two-dimensional spectral images. The data obtained by our method is small and therefore convenient for storing and transmitting spectral images. There are still some open questions in our system to be investigated, for example the choice of the color filter set, possible system noise, near singularity of the inverse matrix and the size of the light area to be illuminated. The main result of this paper is a prototype of the spectral vision system, which can be developed further to be more accurate in its color representation. The optical system can be used to calculate the optical inner product, and therefore this system can be used in various optical pattern recognition tasks, in which the algorithm contains the inner product calculation.

ACKNOWLEDGMENTS

This work was done when Markku Hauta-Kasari was visiting researcher at the Graduate School of Science and Engineering, Saitama University, Japan. Markku Hauta-Kasari was supported by the scholarships from the Monbusho (Japanese Ministry of Education) and from the Lappeenranta University of Technology, Finland. This work was also partly supported by the Grant-in-Aid for Development Scientific Research (B) (No. 10555013) of the Japanese Ministry of Education. The Munsell spectral database is available at the www-server of the Lappeenranta University of Technology, Finland, `http://www.it.lut.fi/research/color/lutcs_database.html`. Markku Hauta-Kasari was supported by the travel grant from the Finnish Cultural Foundation, which is gratefully acknowledged.

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Low-dimensional multispectral image analyzing system with optimized broad-band filters

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Abstract

Low-dimensional subspace constructed by learning algorithms is optically implemented as optimized broad-band filter functions. Two types of the system will be presented: (1) active-type system or spectral synthesizer in which spectral intensity of illuminating light is controlled by an optical system including a liquid crystal spatial light modulator (LCSLM), (2) passive type system in which rewritable filters having spectral transmittances of the optimized filter functions are implemented by a device coupled of an LCSLM and a linear variable filter. Experiments of spectral estimation of a color image with four filter functions optimized by Munsell color database will be shown.

Introduction

Spectral image analysis has recently been progressed more and more. It is used in many fields of science and engineering for machine vision, telemedicine, agrobiology, art painting reproduction, and so on. Spectral images can be obtained, for example, with a CCD camera through narrow-band interference filters[1], an acousto-optical tunable filter[2], a liquid crystal tunable filter[3], a prism-grating-prism based line camera[4], or Fourier-transform-based methods[5]. In these multispectral methods, spectral images are measured precisely for each wavelength range. In any case, however, huge multi-images have to be taken serially. Any a kind of scanning mechanism is required. After multi-spectral image data are acquired, necessary information will be extracted by analytical or statistical methods.

Most of the multispectral image analysis is finally used to distinguish the object under pertinent rules or criteria and is not necessary to know low data of spectral distribution. In many cases, statistical characteristics of the objective spectral database can be known experientially in advance. If we can construct a subspace which reflects spectral characteristics of the object and implemented by something like a set of small number of filters, only inner products between filter functions and the object spectrum will give important information which is enough to classify of parametalize the object in expected spectral bands. Parallel and fast data acquisition become possible if the number of filters are few enough. Our final goal is to establish such an intelligent eye.

In this paper, we want to introduce (1) a subspace method and filter optimization method to reduce degree of multiplex of spectral data of the Munsell color database, (2) implementation of filter functions, and (3) spectral estimation of objects by the proposed system.

Design of broad-band color filters

Vector subspace method based on principal component analysis[6] is one of the promised way to reduce degree of multiplex of spectral data. A spectrum is expanded on a low-dimensional subspace spanned by orthogonalized basis functions calculated from a correlation matrix of the database containing objective color samples[7,8]. In our previous work, color spectra measured from Munsell book of color[9] can be represented accurately by 3-8 basis vectors produced by the subspace method. Due to the orthogonality of basis vectors, however, they contain both positive and negative elements. It is difficult to implement these vectors in optical components directly. On the other hand, filter functions which contain only positive elements can be designed by an optimization technique[10,11] using an unsupervised neural network instead of a subspace method. The neural network clusters color spectra in a database into some discrete number of groups.

After learning, the vectors corresponding to the centers of the clusters are used as color filter functions. Four color filter set was designed over the unsupervised neural network for the database of 1269 Munsell spectra. The number of color filters is determined by the required accuracy in each application. Theoretically, the more filters are used, the more accurate the spectral estimation becomes. In practice, increase in the number of filters does not always lead experimentally to improve the estimation accuracy.[12,13] The optimal number of filters was determined experimentally[12]. It is also important what kind of database we should use for filter design. The database of the 1269 Munsell spectra covers the color space widely, and we consider that the filter set designed for the database can be used to estimate not only the Munsell spectra but also spectra of natural objects.[17] Therefore, we used the database of the 1269 Munsell spectra. Note that if spectra of objects whose colors cover a narrower color space are estimated, the unsupervised neural network should be retrained for other database which covers the corresponding color space instead of the Munsell database. It is easy to retrain new filters by the unsupervised neural network.

Figure 1 shows a set of the four filter functions which we used. The filter function (a) is almost average curve of the database of the 1269 Munsell spectra. Each filter function of (b) to (d) has a gentle peak in a different wavelength range. It means that each filter function is independent of each other. In order to obtain inner products between a spectrum of an object and designed broad-band color filter functions optically, there are two ways as is shown in Fig. 2: (a) active type and (b) passive type. In the active type, intensity images of an object illuminated by synthesized lights having spectra of designed filter functions are taken with a CCD camera.[18-20] This method is useful for indoor measurement such as micrographs, but it is not easy to apply it to measuring samples illuminated by an arbitrary light source such as the sunlight in outdoor measurement. In such a case, a passive type shown in Fig. 2 (b) is required. In this method, intensity images of an object are taken through broad-band filters corresponding to the designed filter functions. In this paper, we introduce how to implement (1) spectral synthesizer for active type system and (2) rewritable transparent filters for passive type system. Spectral estimation results will be shown for the passive-type system.

The set of color filter functions is non-orthogonal and the spectral estimation is done by using a pseudoinverse matrix:

$$s' = W(W^T W)^{-1} W^T s, \qquad (1)$$

where s is a spectrum of an object and W is the matrix of the color filter set. In optical implementation, the inner products $W^T s$ are determined experimentally.

Active-type system --- spectral synthesizer

In the active-type system, an object to be observed is illuminated by the light which has a spectral characteristics of the color filter W_i. Then the detected intensity of the sample corresponds to the inner product $W_i^T s$. To synthesize the light corresponding to the color filter, we constructed the optical setup for the spectral synthesizer shown in Fig.3. The white-light source is a halogen lamp. The light is introduced to a slit by a fiber light guide, which is mixed in the figure and then is reflected by a mirror and is incident on a concave grating. On the dispersion plane there are a rectangular window, a cylindrical lens, and a liquid-crystal panel. The transmittance of the LC panel along the wavelength axis is controlled by a computer through a monochrome image board and an LC driver. The light passing through the LC panel is finally mixed by the second concave grating. Mixed light from the second grating is directed to the measuring plane by a mirror.

In our experiments we controlled the spectral intensity of the synthesized light from 400nm to 700nm. Transmittance patterns corresponding to the four filter functions in Fig.1 are written on the LC panel. These patterns were programmed one by one to the LC panel, and the output spectra were measured by the CCD camera with 31 narrow-band filters. Figure 4 shows the results of the measurements of the spectra of the synthesized lights compared with that of the designed light. The solid curves are the designed filter set multiplied by the light-source spectrum and the dotted curves are the measured output spectra which this light source is used. It can be seen that the system can synthesize the illumination corresponding to each color filter with sufficient accuracy.

Passive-type system --- rewritable broadband transparent filter

In the passive-type system, intensity images of an object are taken through broad-band filters corresponding to the designed filter functions. An experimental setup for a proposed rewritable broad-band color filter system is shown in Fig. 5. An intensity image of an object illuminated by a white light source is taken with a CCD camera through a filter part. The filter part consists of an LC panel and a linear variable filter (LVF), and both components were attached together. The LVF is a kind of interference filter in which the central wavelength of transmitting light varies 400 to 700 nm linearly depending on the position of the plate. A spatial filter pattern which corresponds to a designed color filter function is written on the LC panel along the wavelength axis of the LVF. The key device of this system, that is, the combined filter part of the LVF and the LC panel was mounted on a linear stage placed right in front of the lens aperture of the CCD camera. The combined filter part was set as close as possible to the lens. The wavelength axis of the LVF is parallel to the moving direction of the linear stage.

A spatial filter pattern which corresponds to a designed color filter function was written on the LC panel. The filter system was operated to implement four filter functions. The resultant intensities through the filter system were taken with the CCD camera through 31 narrow-band filters ranging 400 to 700 nm at 10-nm intervals. Figure 6 shows the experimental results. Solid lines are the normalized spectral intensity of the light through the implemented filters. Dashed lines are the normalized expected curves which are the products between the four color filter functions in Fig. 1 and the spectral intensity of the white light source. Implemented spectral intensities almost coincided with expected ones.

To evaluate the accuracy of this system, we calculated three error parameters, which are norm errors, CIE xy errors, and ΔE^* values for CIE L*a*b* errors. Averaged norm error, averaged CIE xy error and averaged ΔE^* value of four filters were also calculated and shown at the bottom of Table 1. The maximum ΔE^* value is below 5.0 and averaged ΔE^* value is below 2.5. The results show that the proposed filter system works well as a broad-band color filter and the implemented color filters have sufficient accuracy.

Table 1 Comparison of the norm error, the CIExy error, and the CIE L*a*b* error for four samples for the expected filters and the spectral intensities of the light through the implemented filters.

	norm	CIE xy				CIE L*a*b*			
Sample	Error	p(x)	o(x)	Δx	Error	p(L*)	o(L*)	Δ L*	Error (ΔE*)
Number		p(y)	o(y)	Δy		p(a*)	o(a*)	Δa*	
						p(b*)	o(b*)	Δb*	
1	4.38	0.3275	0.3319	0.0044	0.0023	55.68	55.63	0.05	1.44
		0.4092	0.4091	0.0001		-17.17	-15.84	1.33	
						19.85	20.39	0.54	
2	5.55	0.2629	0.2634	0.0005	0.0015	54.00	54.15	0.15	0.73
		0.4134	0.4158	0.0025		-37.80	-38.22	0.42	
						12.53	13.11	0.58	
3	4.23	0.3815	0.3820	0.0005	0.0039	57.40	57.23	0.17	2.49
		0.4832	0.4759	0.0073		-18.95	-17.26	1.69	
						46.04	44.21	1.83	
4	7.29	0.4136	0.4259	0.0123	0.0095	52.66	51.80	0.86	4.65
		0.3923	0.3857	0.0066		10.43	15.00	4.57	
						27.35	27.40	0.05	
Average	5.36				0.0043				2.33

Spectral estimation by the passive-type system

The proposed system was applied to estimate spectra of natural objects in a two-dimensional image. Experiments of spectral estimation were done for the active- and passive system. Here only a result of the passive-system to observe an image of grasses under sunlight illumination is shown. To monitor the spectrum of the sunlight, reflected light of a standard white board of $BaSO_4$ which was placed near the object scene was measured by spectral radiometer.

Figure 7 shows four intensity images of the scene, which were taken through the four implemented color filters, respectively. From a set of the four intensity images, a spectrum in the two-dimensional image was estimated for each pixel on the wavelength range of 400 to 700 nm at 10-nm intervals using a pseudoinverse matrix in Eq. (1). The estimated spectrum in the two-dimensional image was compared with that measured by the conventional multispectral imaging method. For this purpose, 31 intensity images of the test scene were taken through 31 narrow-band filters ranging 400 to 700 nm at 10-nm intervals under the transparent condition of the system where all the input level to the LC panel was set to 255.

Figure 8 shows four results of the spectra at different locations in the scene. Dashed curves are estimated spectra from a set of the four intensity images obtained in the proposed system, and solid curves are spectra measured by the multispectral method with 31 narrow-band filters.

In these results, shapes of the estimated spectral are correlated to those obtained by the multispectral method. However, we were faced with problems that the estimated spectra fluctuated widely and had unreasonable negative elements in some parts. The problem is considered to be caused by calculation of the pseudoinverse matrix applied to the optically calculated inner products. The inverse matrix in Eq. (1) sometimes becomes near singular, then a very small error between the optically calculated inner product and the expected inner product causes large estimation errors.

Conclusions

We proposed low-dimensional multispectral image analyzing system with optimized broad-band filters which were implemented as the active-type and passive-type systems. The proposed filter system implemented color filters with expected accuracy. However, we cannot say that the spectral estimation was done with sufficient accuracy. We consider that the error for spectral estimation was caused by the calculation of a pseudoinverse matrix to the inner product optically obtained. One possibility to overcome the problem is to apply basis vectors designed by subspace method to our optical system. In this case positive and negative parts of inner products have to be taken separately and difference of two inner products should be calculated[14].

But our final goal is not for spectral estimation but for intelligent classification of spectra as described in the first chapter. Intelligent classifer requires to obtain inner products between filter functions and the object spectrum accurately. The experiments seems to satisfy this condition. The shape of filter functions or sensitivity of the photoreceptors of the intelligent eye can be changed according to our purposes by selecting spectral database.

Acknowledgements

This study is supported by the Grant-in-Aid for Developmental Scientific Research (B) (No.10555013) of the Japanese Ministry of Education. This study is also supported by the Toyota High-tech Research Grant Program. The Munsell spectra database is available at the www-server of the University of Joensuu, Finland, http://cs.joensuu.fi/~spectral/.

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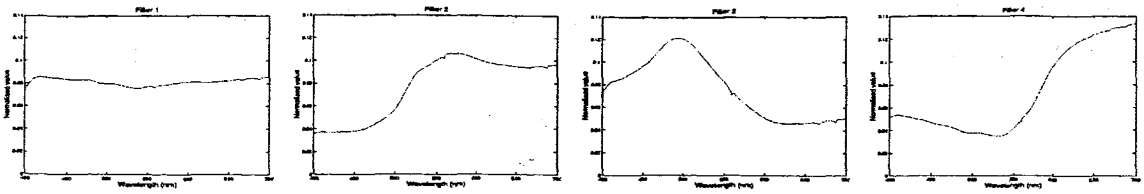
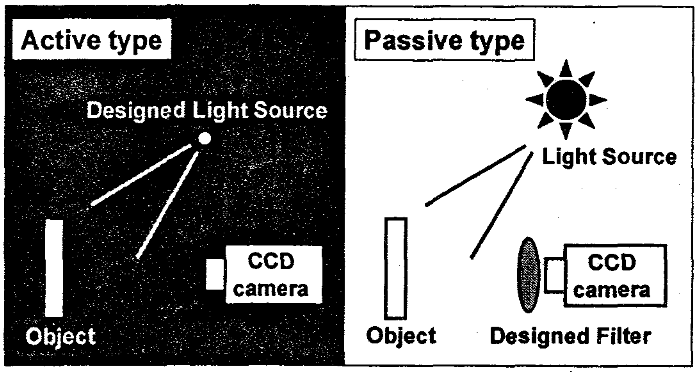


(a) (b) (c) (d)

Fig. 1. A set of four color filters designed over the unsupervised neural network.



(a) (b)

Fig. 2. Two ways to obtain inner products between a spectrum of an object and designed broad-band color filter functions optically.

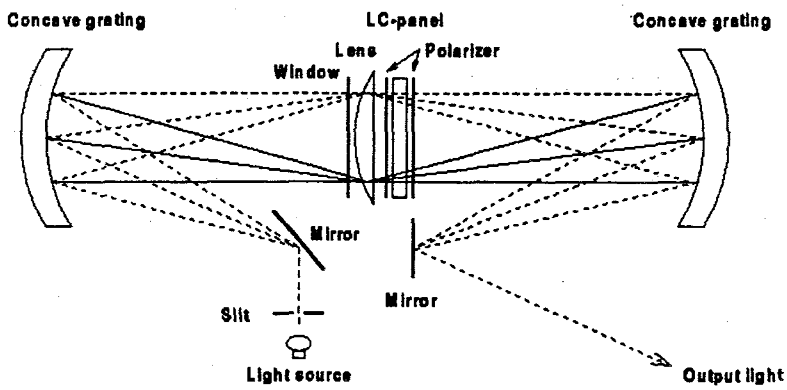


Fig. 3. Optical setup for spectral synthesizer.

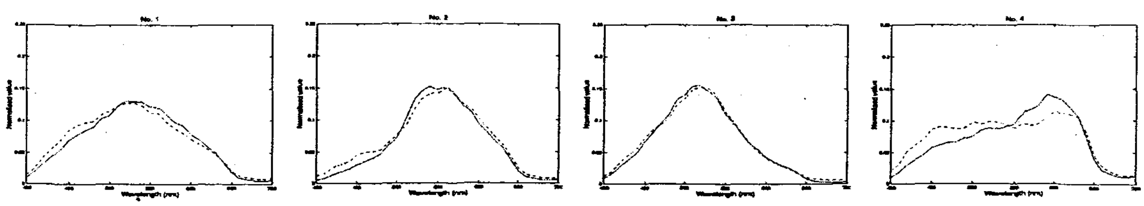


Fig. 4. Solid lines are the designed filters multiplied by the light source spectrum and dotted lines are measured results.

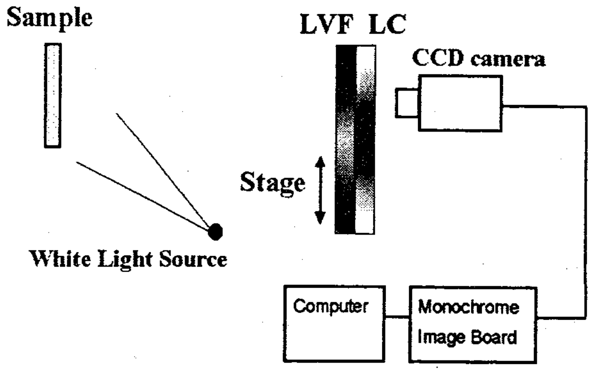


Fig. 5. Optical setup for broadband rewritable filters.

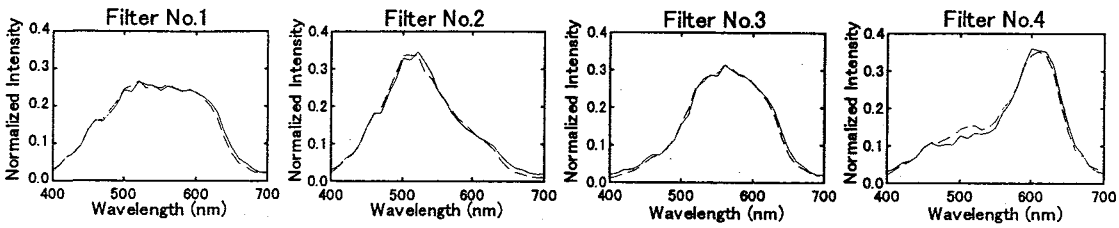


Fig. 6. Dashed lines are the designed filters multiplied by the light source spectrum and solid lines are measured results.

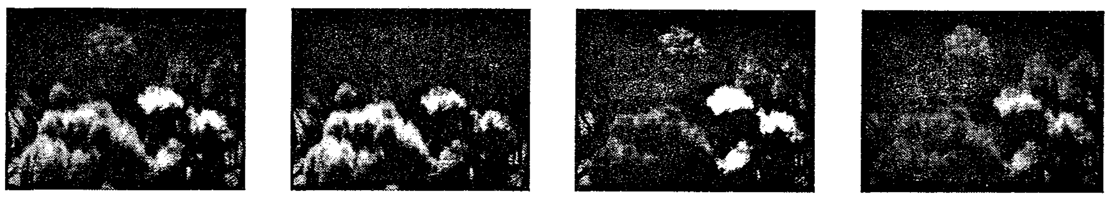


Fig. 7. Four intensity images taken through the four implemented color filters.

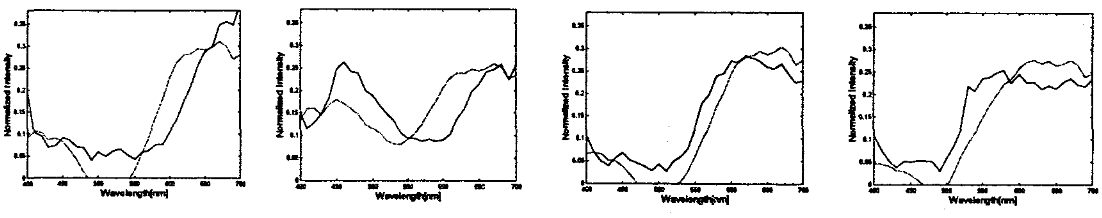


Fig. 8. Four measured results of spectra at different locations in the scene. Dashed lines are estimated spectra from a set of the four intensity images and solid lines are spectra measured by the multispectral method with 31 narrow-band filters.

Spectral Image Analysis of a natural color sample using Rewritable Transparent Broad-band Filters

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ABSTRACT

In this study, we propose an optical transparent broad-band filter system which can be used to estimate a color spectrum and two-dimensional spectral images. The filter function of this system can be rewritten arbitrarily. Spectral distribution of a natural color sample can be represented by a set of inner products between broad-band color filter functions and the spectral distribution of a sample. In our system, a test image is observed through the filter part consists of a liquid crystal spatial light modulator (LCSLM) and a linear variable filter (LVF) attached together. The intensity image of a sample is taken while the combined device (LCSLM and LVF) is moving just in front of the lens aperture of the monochrome CCD-camera. From the detected intensity images corresponding to the inner products, the color spectra of the sample were reconstructed using a pseudoinverse matrix. The data obtained from the filtering process is only four monochrome images. It is convenient for storing and transmitting the spectral image. We also applied this system to outdoor measurement under sunlight illumination. The experimental results of estimating a color spectrum and two-dimensional spectral images are presented.

1. INTRODUCTION

Spectral image analysis is becoming more important in the field of environmental monitoring,[1,2] thus the need of outdoor measurement is increasing. Spectra of natural color samples such as leaves and agricultural products have smooth shape which strongly correlate each other.[3,4] Spectral distribution of such an object can be expanded by a set of broad-band color filter functions, so it can be represented by a set of inner products between the spectral distribution of the object and the color filters corresponding to the broad-band color filter functions.

Subspace method[5] which is based on KL-expansion has been successfully used to represent the spectral distribution with a few of basis vectors experimentally.[6,7] However, due to the orthogonality of the eigenvectors, the corresponding color filters usually contain negative elements and cannot be implemented in optical components directly. Hauta-Kasari et al.[8] proposed design of a low-dimensional broad-band color filter set using the unsupervised neural network. The color filters contain only positive elements and can be directly used in optical implementation.

There are two ways to obtain inner products between the spectral distribution of a sample and broad-band color filter functions. One approach is based on a spectral synthesizer method which can be used to take intensity images of a sample illuminated by synthesized lights corresponding to the spectral characteristics of the color filters.[6,7,9] This method is useful for indoor measurement, but it is difficult to apply it for measuring samples illuminated by an arbitrary light source like the sun. Another approach is to take intensity images of a sample through optical transparent broad-band color filters corresponding to the broad-band color filter functions. This method is simple and can be used for outdoor measurement. But actually, it is difficult to make optical transparent broad-band color filters whose transmitting wavelength can be rewritten corresponding to the designed broad-band color filter functions.

Recently some methods of spectral estimation using broad-band filters have been proposed.[10-14] However, these broad-band filters are RGB-type or Gaussian-type in shape and the transmitting wavelengths are fixed. These kind of broad-band filters can not be used for our method.

To overcome this problem, in this paper, we propose a new system to implement rewritable optical transparent broad-band color filters. We applied this system to acquire a color spectrum and two-dimensional spectral images.

2. COLOR FILTER FUNCTIONS

We used the broad-band color filter set with positive elements designed by the unsupervised neural network[4] in which database of the 1269 Munsell[15] spectra was used in the learning phase. In this study we used the filter set of four filters. The detailed description of the color filter design can be found in Ref.8.

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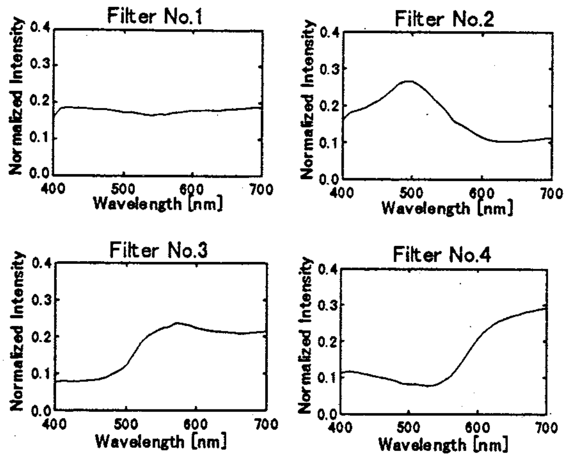

Figure 1. Broad-band color filter set.

Figure 1 shows the color filter set used in this study. The color filter set is non-orthogonal and the spectrum s' is reconstructed by using a pseudoinverse matrix:

$$s' = W(W^TW)^{-1}W^Ts, \qquad (1)$$

where W is the color filter set and $W(W^TW)^{-1}$ is known. In the optical implementation, the inner products W^Ts between the color filter set W and the sample's spectrum s can be determined optically.

3. EXPERIMENTS AND RESULTS

3.1 Broad-band filter system

Figure 2 shows an experimental setup for an optical transparent broad-band filter system. In this experiment, the system was tested in a darkroom. An intensity image of a sample illuminated by a white light source is taken by a monochrome CCD-camera through a filter part. The filter part consists of a liquid crystal spatial light modulator (LCSLM) and a linear variable filter (LVF). The LVF is a kind of interference filter whose transmitting wavelength is linearly varied from 400nm to 700nm depending on the position parallel to the moving direction of the linear stage. Spatial filter pattern corresponding to the broad-band color filter function was written on the LC-panel along to the wavelength axis of the LVF. Both components were attached each other and mounted on a linear stage. The shutter of the monochrome CCD-camera is opened for a period while the combined device (LCSLM and LVF) is moving just in front of the lens aperture of the monochrome CCD-camera. In this system, we can make any color filters only by changing the input pattern on the LCSLM.

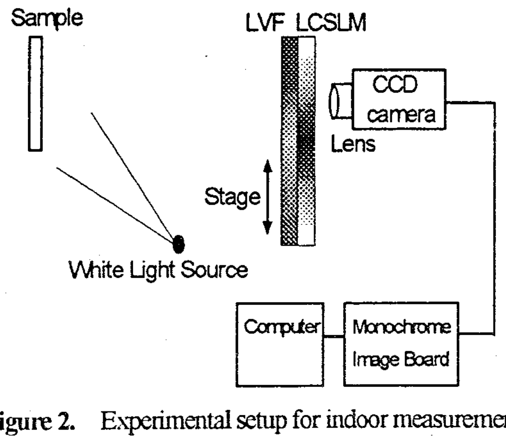

Figure 2. Experimental setup for indoor measurement

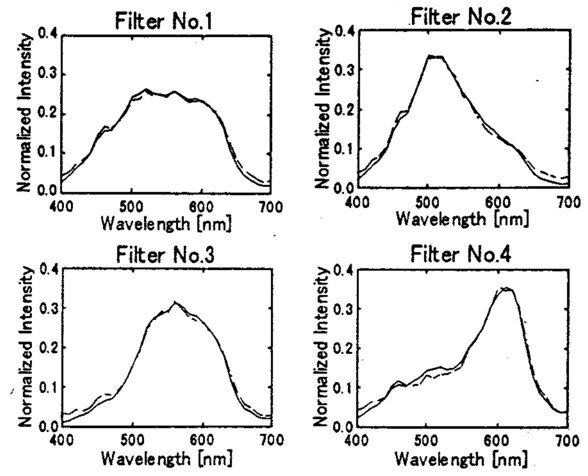

Figure 3. Experimental results. Solid lines are the expected filter functions and dashed lines are the optically implemented filters.

To investigate the validity of this system, the intensity images for the spectral distribution were measured through 31 narrow band interference filters from 400nm to 700nm at 10nm intervals. In this experiments, a standard white board of $BaSO_4$ illuminated by a halogen lamp was observed through the proposed filter system. The average intensity inside the window of 10 × 10 pixels was calculated to obtain the spectral distribution. Figure 3 shows the experimental results. Solid lines are the expected filter functions which is the product between the four filter functions and a light source spectrum, and dashed lines are the spectral distributions of the optically implemented filters. Both distributions almost coincide within average error of 5.4%.

3.2 Spectrum reconstruction (Indoor measurement)

We applied this system to reconstruct spectral images. Real world object, which is a strawberry, a kamquat (a fruit like an orange) and four color sheets (blue, green, yellow, red) were used as test samples in one image. The test samples were set in darkroom and illuminated by the halogen lamp. The intensity images of the sample through the color filter set of four filters were obtained by the monochrome CCD-camera. From the four intensity images, the spectral images were reconstructed in each pixel on the wavelength range from 400nm to 700nm at 10nm intervals using a pseudoinverse matrix in Eq.(1). To compare the results, we obtained the spectral images of the same sample by the monochrome CCD-camera with 31 narrow-band interference filters from 400nm to 700nm at 10nm intervals. Figure 4 shows the four examples of spectra at the different locations of the spectral images. Solid lines are the measured spectra with 31 narrow-band interference filters, and dashed lines are the reconstructed spectra from four intensity images obtained by the proposed system.

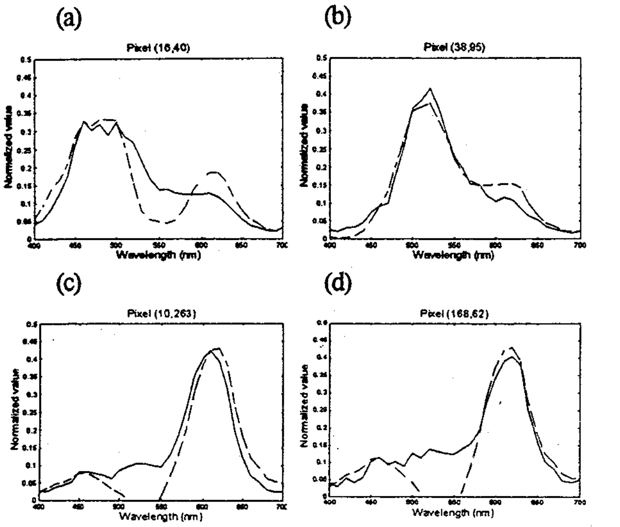

Figure 4. The spectra at the different locations of the spectral image. (a)Blue color sheet (b)Green color sheet (c)Red color sheet (d) Strawberry.

3.3 Spectrum reconstruction (Outdoor measurement)

In the next experiment, we applied this system to outdoor measurement under sunlight illumination. An experimental setup for outdoor measurement is shown in Fig.5. Some plants with flowers illuminated by sunlight were used as samples in one image. In this experiment, the sunlight spectrum was monitored while the intensity images of the samples were obtained through the four filters by the proposed system. The spectral distribution of a standard white board of BaSO4 which was set near the samples was measured by spectroradiometer. The measured spectrum was used for spectrum reconstruction.

Because it takes about 20seconds both to measure the sunlight spectrum by the spectroradiometer from 400nm to 700nm, and to obtain four intensity images of a sample by the proposed system, the experiment have to be done while the sunlight intensity does not change at least for 20seconds. So the experiment was done in daytime under clear weather without a cloud and a wind.

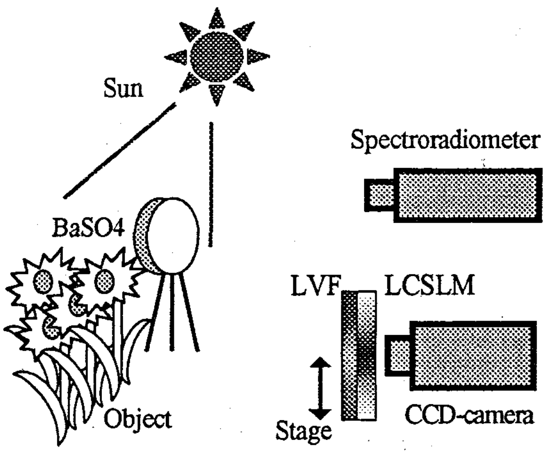

Figure 5. Experimental setup for outdoor measurement.

From the obtained four intensity images through the proposed four filters, the spectral images were reconstructed same as Section3.2, and also compared with the spectra obtained by the monochrome CCD-camera with 31 narrow-band interference filters. Both distributions were divided by each light source spectrum. Figure 6 shows two examples of spectra at different locations of the spectral image. Fig.6 (a) is the spectrum of an orange marigold petal, and Fig.6 (b) is the spectrum of a red flower. Solid lines are the measured spectra with 31 narrow-band interference filters, and dashed lines are the reconstructed spectra from four intensity images obtained by the proposed system.

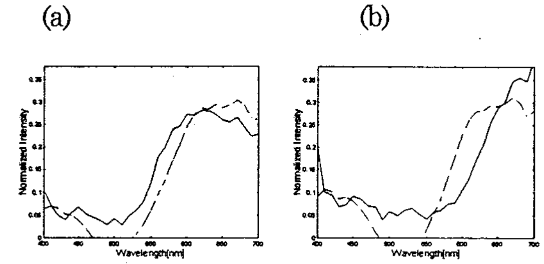

Figure 6. The spectra at the different locations of the spectral image. (a) an orange marigold petal (b) a red flower.

4. DISCUSSION AND CONCLUSIONS

We proposed the optical transparent broad-band filter system which can be used to estimate a color spectrum and two-dimensional spectral images. The proposed system could be realized by using the combination of the LCSLM and the LVF. The transmittance of the filter function of this system can be rewritten arbitrarily only by changing the input pattern on the LCSLM.

In Section 2, we briefly explained the color filter functions we used and how to reconstruct spectral distributions. In Section 3.1 our experimental setup was introduced. We investigated the validity of this system. The spectral distribution of the intensity image through the proposed filter system almost coincided with the expected filter functions. The accuracy of this system is comparable to the spectral synthesizer system in Ref.9. In Section 3.2, we applied this system for a real world object to reconstruct spectral images from obtained four intensity images using a pseudoinverse matrix. In this experiment, the system was tested in darkroom and the samples were illuminated by the halogen lamp. The acquired spectra were compared to the spectra measured by the monochrome CCD-camera with 31 narrow-band filters. The spectra obtained by the both method correlated well. This results show that the spectrum of real world object color can be reconstructed by our system. In Section 3.3, this system was applied to outdoor measurement under sunlight illumination. In this measurement, the sunlight spectrum was monitored by spectroradiometer and used for spectrum reconstruction. The spectral images were reconstructed same as Section3.2. The acquired spectra were compared to the spectra measured by the monochrome CCD-camera with 31 narrow-band filters. Also in the case of outdoor measurement, the spectra obtained by the both method correlated well.

We can say that our system can be used under arbitrary illuminating conditions such as sunlight. There is a possibility that this system can be applied to remote sensing. In this paper, the amount of data obtained from the filtering process is only four monochrome images. It is convenient for storing and transmitting the spectral image.

ACKNOWLEDGMENTS

This study was supported by the Grant-in-Aid for Developmental Scientific Research (B) (No.10555013) of the Japanese Ministry of Education. This study was also supported by the Toyota High-tech Research Grant Program. The Munsell spectra database is available at the www-server of the Lappeenranta University of Technology, Finland, http://www.it.lut.fi/research/color/lutcs_database.html.

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Spectral Vision System based on Rewritable Broad Band Color Filters

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Abstract

We present a prototype of the spectral vision system that can be used to measure a color spectrum and two-dimensional spectral images. First we designed a low-dimensional broad band color filter set with a constraint of positive spectral values by a computational technique based on an unsupervised neural network. Then we constructed a compact size optical setup for the spectral synthesizer, which can be used to synthesize the light corresponding to the spectral characteristics of the color filter. We implemented the color filters optically using a liquid crystal spatial light modulator (LCSLM). In our experiments we illuminated a sample of a real world scene by the synthesized lights and detected the optically calculated inner products by a CCD-camera. The amount of data obtained from the filtering process is only a few monochrome images, which can be used to store and transmit a spectral image conveniently. From the detected inner product images we reconstructed the sample's color spectra using a pseudoinverse matrix. We present the experimental results of measuring a spectral image by our spectral vision system.

1. INTRODUCTION

Recently, the use of spectral imaging has been the focus of growing interest in the field of high-quality color image analysis. The spectral imaging systems have application areas such as remote sensing, environmental monitoring, material analysis, computer vision, digital archives, and industrial quality control. The spectral based representation of color avoids the problem of metamerism,[1] which may exist in the human color vision system based three-dimensional color vision models. When the spectral imaging system is tuned to measure the visible light, then the measured image represents a high-quality color image, in which every pixel contains a color spectrum.

To measure spectral images, devices such as a CCD-camera with narrow band interference filters,[2] an acousto-optical tunable filter (AOTF),[3] Fourier transform based interferometric imaging system,[4] a liquid crystal tunable filter (LCTF)[5] or a prism-grating-prism (PGP) based line scanning camera[6] can be used. Currently there are two basic approaches to measure spectral images. One approach is based on the acquisition of a two-dimensional image at different wavelengths at different times.[2,5] Another approach is based on the acquisition of line images with a simultaneous measurement of spectra at different wavelengths by scanning a camera or an object along the spatial axis.[6] All these systems produce a large amount of data to be stored or transmitted.

It has been shown that the color spectra can be reproduced accurately from a low-dimensional representation of spectra.[7–9] One approach to compress spectra is to have measured spectra and compress them by software.[10,11] Another approach is to design the low-dimensional spectral imaging system so that only a few optical color filters are used to acquire the optimal component image set for the spectral reconstruction.[12–14] The low-dimensional component image set can be directly used to store and transmit spectral images effectively, and it can be also directly used in pattern recognition tasks.

Recently, we proposed two prototypes of the low-dimensional spectral imaging system.[15,16] The color filters in these prototypes are rewritable and the filter effect on a sample is produced as follows. The prototype presented in this paper is based on the spectral synthesizer, which is used to illuminate the object by the light, which has the spectral characteristics of the

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color filter. Another prototype[16] filters the reflecting or transmitting light from an object by a combined filter part, which consists of a linear variable filter (LVF) and a liquid crystal spatial light modulator.

The paper is organized as follows. In Section 2 we briefly review the color filter design from our previous study. Then in Section 3 we introduce the experimental setup for the spectral vision system. In Section 4 we report the experimental results and in Section 5 we discuss our results.

2. COLOR FILTER DESIGN

The color filter design with a constraint of positive spectral values has been under a growing interest recently. The methods for choosing an optimized set of a commercially available Kodak Wratten gelatin color filter set were proposed in Refs. 17–19 and in Refs. 20–23 the positive color filters were designed by computational techniques. In Ref. 24 we proposed a new computational technique based on an unsupervised neural network to design broad band color filters with a constraint of positive spectral values. By our method it is possible to design broad band color filters according to an application. Fig. 1 shows the filter set of 4 filters used in this study. The filter set was designed for the color spectra database of 1269 samples measured from the Munsell book of color.[25]

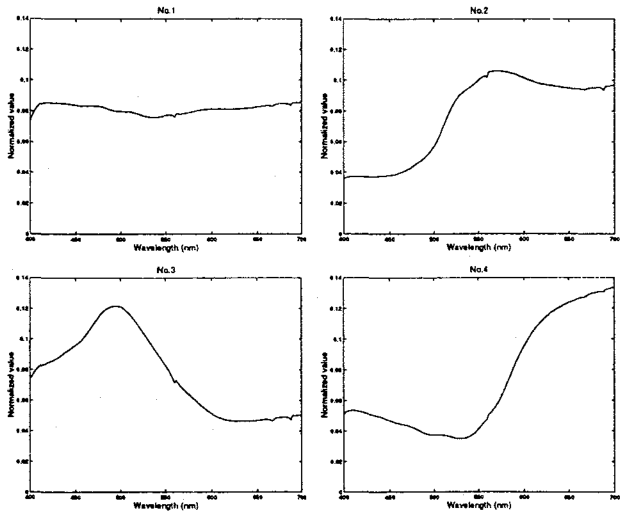

Figure 1. Filter set of 4 learned filters used in proposed spectral vision system.

The designed color filter set is non-orthogonal and to use it to reconstruct a spectrum s, a pseudoinverse matrix can be used:

$$s' = W(W^TW)^{-1}W^Ts, \quad (1)$$

where W is the filter set. In the optical implementation, $W(W^TW)^{-1}$ is known and the inner products, W^Ts, between the filter set W and the sample's spectrum s are determined experimentally.

3. SPECTRAL VISION SYSTEM

The inner products W^Ts in Eq. (1) between a broad band color filter set W and a sample s can be calculated optically using the liquid crystal panel.[12,26] If the sample is illuminated by the synthesized light, which has the spectral characteristics of the color filter W_i, then the detected intensity of the sample corresponds to the inner product W_i^Ts. To synthesize the light corresponding to the color filter, we constructed the optical setup shown in Fig. 2. The experimental setup for the spectral vision system is shown in Fig. 3.

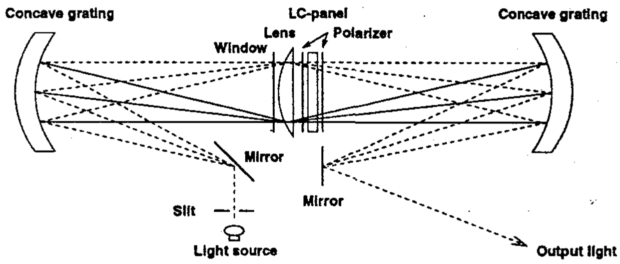

Figure 2. Optical setup for the spectral synthesizer.

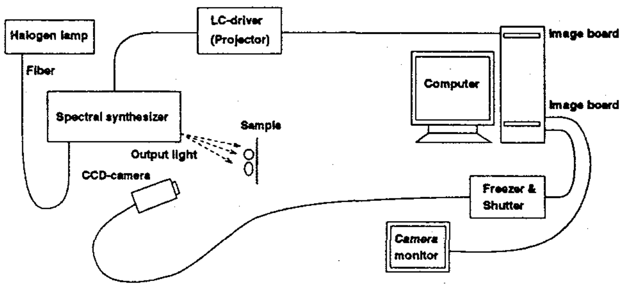

Figure 3. Spectral vision system.

4. EXPERIMENTS

We acquired the spectral image from a real world object by our spectral vision system. As a real world scene shown in Fig. 4 we used a setup of a strawberry and a mandarin lying on a table in front of a colored panel. We illuminated the sample by 4 synthesized lights corresponding to the color filters shown in Fig. 1 and the reflected intensity images shown in Fig. 5 were detected by the CCD-camera.

From the detected intensity images we reconstructed the spectral image in the wavelength range from

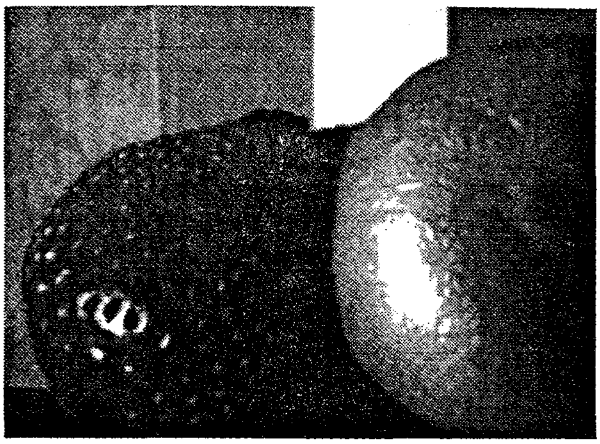

Figure 4. Sample as a real size gray level image, illuminated by the halogen lamp.

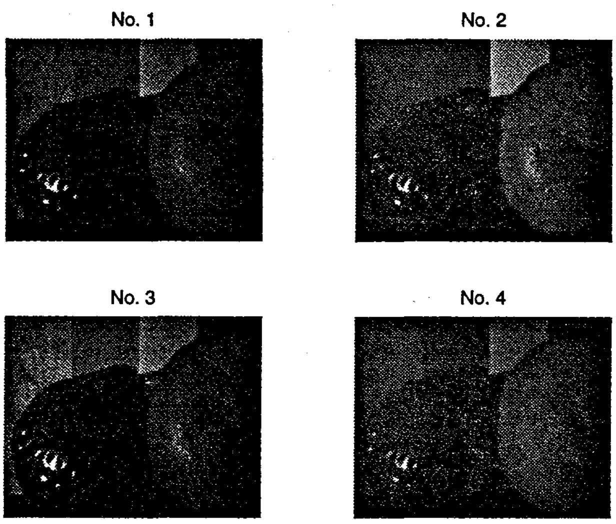

Figure 5. Detected intensity images of the sample, when the sample was illuminated by the synthesized lights, which correspond to 4 color filters.

400nm to 700nm at 10nm intervals using the pseudoinverse matrix in Eq. (1). To compare the results, we measured the same spectral image by the CCD-camera with 31 narrow band interference filters covering the wavelength range from 400nm to 700nm, at 10nm intervals.

Figure 6 shows two examples of spectra at different locations of the spectral image. The spectrum in Figure 6 a) is the spectrum of the glossy yellow color sheet and the spectrum of the strawberry is shown in Figure 6 b).

5. DISCUSSION

We presented a prototype of the spectral vision system that can be used to measure a color spectrum

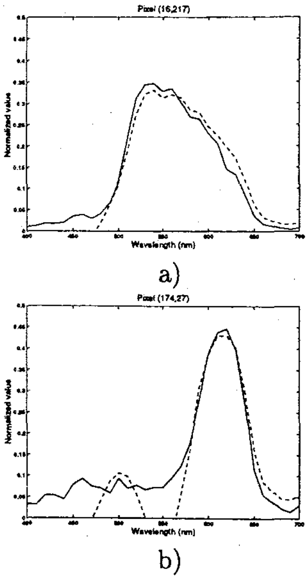

Figure 6. Spectra at two different locations of the spectral image. Solid lines correspond to the spectral image measured by CCD-camera with 31 narrow band filters and dashed lines correspond to the spectral image measured by the spectral vision system using 4 filters.

and two-dimensional spectral images. The rewritable broad band color filters were implemented using the LCSLM. We illuminated the sample with synthesized light, and therefore our system is limited to indoor measurements. The amount of data obtained from the filtering process is small and therefore convenient for storing and transmitting spectral images. There are still some open questions in our system to be investigated, for example, the choice of the color filter set, possible system noise, near singularity of the inverse matrix and the size of the light area to be illuminated. The main result of this work is a prototype of the spectral vision system, which can be developed further to be more accurate in its color representation. The optical system can be used to calculate the optical inner product, and therefore this system can be used in various optical pattern recognition tasks, for example in classifiers, where the classification criteria contain the inner product calculation.

ACKNOWLEDGMENTS

This work was done when Markku Hauta-Kasari was visiting researcher at the Graduate School of Science and Engineering, Saitama University, Japan. Markku Hauta-Kasari was supported by the scholarships from the Monbusho (Japanese Ministry of Education) and from the Lappeenranta University of Technology, Finland. This work was also partly supported by the Grant-in-Aid for Developmental Scientific Research (B) (No. 10555013) of the Japanese Ministry of Education and the Toyota High-tech Research Grant Program. The Munsell spectral database is available at the www-server of the Lappeenranta University of Technology, Finland, *http://www.it.lut.fi/research/color/lutcs_database.html.*

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Rewritable Broad-band Color Filters for Spectral Image Analysis

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(Received December 14, 2000; Accepted January 4, 2001)

We propose an optical system to implement rewritable transparent broad-band color filters. The filter consists of a linear variable filter and a liquid crystal spatial light modulator in which an expected filter function is written. A time-integrated intensity image was taken while the filter was passing the lens aperture of a CCD camera. The averaged norm error between the implemented and the expected filter functions was about 5.4%. The system was applied to spectral estimation in a two-dimensional color image.

Keywords: spectral imaging system, rewritable broad-band color filter, linear variable filter, liquid crystal spatial light modulator.

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1. Introduction

Color contains important information on materials, and methods for quantification of color have been explored. In color research, three-dimensional color coordinate systems have been traditionally used. These systems, however, have a metamerism problem[1] in which several different spectra result in the same three-dimensional coordinate. On the other hand, spectra which include many components corresponding to each wavelength range are free from the metamerism problem, and for this reason accuracy is high.

Spectral image analysis has recently progressed rapidly, and is now used for machine vision, telemedicine,[2] agrobiology,[3] art painting reproduction,[4-6] and so on. Environmental monitoring using remote sensing also has received a great deal of attention,[7,8] and requirements for outdoor measurement have been increasing. Spectral images can be obtained, for example, with a CCD camera through narrow-band interference filters,[9] an acousto-optical tunable filter,[10] a liquid crystal tunable filter,[11] a prism-grating-prism based line camera,[12] or Fourier-transform-based methods.[13] In these multispectral methods, spectral images are measured precisely for each wavelength range. Whatever technique is used, however, many images have to be taken, depending on spectral resolution, and copious image data have to be processed and stored.

To compress spectral data, there is a way to design a low-dimensional filter set and obtain low-dimensional compressed data that include optimal components for spectral estimation. Fortunately, spectral components of natural objects strongly correlate with each other. For this reason, a low-dimensional broad-band filter set instead of a narrow-band filter set is used for spectral estimations of natural objects.

For spectral estimation from low-dimensional data, the vector subspace method[14] or the

Wiener method[3,5] is used. In the former, based on principal component analysis, a spectrum is expanded into a subspace spanned by orthogonalized basis functions calculated from correlation matrix of a database containing objective color samples. A spectrum of an object can be represented by a set of inner products between that spectrum and a set of basis functions. Parkkinen et al.[15] calculated several basis vectors by the subspace method for a spectral database containing 1257 samples measured from the Munsell Book of Color.[16] These basis vectors could describe not only spectra belonging to the database but also those of natural objects.[17] Instead of implementation of transparent broad-band filters, Jaaskelainen et al.[18] proposed that lights having the spectra of the basis vectors be synthesized. If the synthesized light illuminates an object, reflected or transmitting light corresponds to an inner product between the spectrum of the object and the synthesized light. Hayasaka et al.[19] applied the spectral synthesizer to micrographs, and estimated transmittance spectra of organs of a mouse using seven images of inner products. Hauta-Kasari et al.[20] designed a compact spectral synthesizer, and estimated reflectance spectra of fruit in an image using four images of inner products. The use of a set of a small number of inner products decreases the amount of data considerably. For example, acquiring spectral images ranging 400 to 700 nm at 10-nm intervals, only four[20] to seven[18,19] images of inner products are required, while 31 images have to be measured in conventional multispectral methods.

There are two ways to obtain inner products optically between a spectrum of an object and computationally designed broad-band color filter functions as shown in Fig. 1: (a) active type and (b) passive type. In the active type, intensity images of an object illuminated by synthesized lights having spectra of designed filter functions are taken with a CCD camera.[18-20] This method is useful for indoor measurement such as micrographs, but it is not easy to apply it to measuring samples illuminated by an arbitrary light source such as the sunlight. For outdoor measurement, the passive type shown in Fig. 1 (b) is required; in this method, intensity images of an object are taken through broad-band filters corresponding to the designed filter functions.

There are some kinds of optical broad-band color filters, such as commercial gelatin broad-band filters,[21,22] a broad-band type liquid crystal tunable filter,[23] and a kind of broad-band filters using dichroic mirrors.[24] Gelatin filters containing a mixture of some kinds of dyes, and a combination of some commercial gelatin filters may realize the filters we want. Transmitting wavelengths of gelatin filters, however, are fixed, and it is impossible to rewrite filter functions flexibly. Other broad-band color filters mentioned above also have little flexibility, making it difficult for them to satisfy our present requirements.

To overcome these problems, we propose a new system to implement rewritable transparent broad-band color filters. The system is the passive type shown in Fig. 1 (b), and spectral transmittance can be changed arbitrarily corresponding to computationally designed filter functions.

The paper is organized as follows: In Section 2 we briefly explain how to prepare broad-band color filter functions and how to estimate spectra. The main topic of this paper is experiments implementing rewritable broad-band color filters in Sections 3, and 4.1. Spectral estimation was done as described in Section 4.2. In Section 5 we give conclusions.

2. Broad-band Color Filter Functions

Low-dimensional basis vectors designed by subspace method based on Karhunen-Loève expansion have been successfully used to estimate original spectra.[15,17-19] Due to the orthogonality of basis vectors, however, they contain both positive and negative elements and cannot be implemented in optical components directly. Two methods can be considered to implement such basis vectors in optical components: (1) multiplying and adding constant values to the basis vectors in order to make every element positive,[18,19] and (2) making two filters for positive and negative elements for each filter function and taking their inner products independently and calculating their difference.[25,26] This, however, leads to more complicated filtering systems.

On the other hand, design of broad-band color filter sets which contain only positive elements was proposed by Lenz et al. using optimization of an energy function based on second- and fourth-order statistical moments,[27] and by Hauta-Kasari et al. using an unsupervised neural network[28] instead of a subspace method. The neural network uses a competitive learning algorithm based on the INSTAR algorithm of Grossberg[29] which was incorporated by Kohonen's[30] self-organizing map with the winner-take-all layer. The neural network clusters color spectra in a database into a discrete number of groups. After learning, the vectors corresponding to the centers of the clusters are used as color filter functions.

In our previous work,[20] a set of broad-band color filter functions was designed over the unsupervised neural network for the database of 1269 Munsell spectra and it was implemented in optical components directly in the active type broad-band filter system. It was used to estimate the original spectra of natural objects. In computer simulations, the accuracy of the filter set for spectral estimation designed over the unsupervised neural network was comparable with that of the basis vector set designed by the subspace method.[28]

In this paper we used the same filter set as that in Ref. 20, i.e., a four color filter set was designed with the help of a neural network trained on a database of 1269 Munsell spectra. The number of color filters is determined by the required accuracy in each application. Theoretically, the larger the number of filters used, the more accurate the spectral estimation becomes. On the other hand, experimentally, increase in the number of filters does not always lead to an improvement in estimation accuracy.[20,21] The optimal number of filters was determined experimentally in our previous work,[20] and in this paper we used that same number, i.e., four.

Figure 2 shows a set of the four filter functions that we used. Filter function (a) is almost the average curve of the database of the 1269 Munsell spectra. Each filter function of (b) to (d) has a gentle peak in a different wavelength range, meaning that each function is independent.

The set of color filter functions is non-orthogonal and the spectral estimation is done using a pseudoinverse matrix:

$$s' = W(W^T W)^{-1} W^T s, \qquad (1)$$

where W is the matrix of the color filter set and $W(W^T W)^{-1}$ takes known quantities. In optical implementation, the inner product $W^T s$ between the color filter set W and the spectrum of an object s corresponds to a set of intensity values at a pixel in a set of intensity images of the object through the color filter set.

The inverse matrix in Eq. (1) sometimes becomes nearly singular,[20,31] then a very small error between the optically calculated inner product and the expected inner product can cause large estimation errors. To decrease the effect of this near singularity, a regularization technique based on truncated singular value decomposition (SVD) was used.

3. Experimental Setup

An experimental setup for a proposed rewritable broad-band color filter system is shown in Fig. 3. An intensity image of an object illuminated by a white light source is taken with a monochrome CCD camera (SONY XC-73, 768×494 pixels) through a filter. The filter consists of a liquid crystal spatial light modulator (LCSLM) (SHARP LQ323Y11 model LC-projector) and a linear variable filter (LVF) (SCHOTT VERIL S60 type), the two components being attached. The LVF is a kind of interference filter measuring 60mm×25mm in which the central wavelength of transmitting light varies 400 to 700 nm linearly depending on the long side position as shown in Fig. 4, and the transmittance is almost uniform in every wavelength range. The liquid-crystal (LC) panel used as a spatial light modulator was that taken from a commercial LC-projector. The screen size of the LC panel was 44.5mm×61.7mm with 234×382 pixels, and the panel was of the active matrix type with thin-film transistors (TFT). A spatial filter pattern that corresponds to a designed color filter function was written on the LC panel along the wavelength axis of the LVF. The key device of this system, that is, the combined filter of the LVF and the LC panel was mounted on a linear stage placed right in front of the lens aperture of the CCD camera. The combined filter was set as close as possible to the lens, and the wavelength axis of the LVF was parallel to the moving direction of the linear stage.

Figure 5 shows a block diagram of the control system for the rewritable broad-band color filter system with the numbers in operating order. The following numbers correspond to the operating order in Fig. 5. An input pattern that corresponds to a designed color filter function is written on the LC panel. The transmittance of the panel is controlled by the computer through a monochrome image board (1) and an LC driver (2). The combined filter mounted on a linear stage is moved at a constant speed. The linear stage is controlled by the computer through an I/O board (3) and a linear stage driver (4). The combined filter passes the lens aperture of the CCD camera while the shutter of the camera is opened; consequently, a time-integrated intensity image is acquired. The trigger-signal is sent to the shutter of the camera by the linear stage driver (5, 6), and the intensity image obtained is stored in the computer through a vision freezer (7) and a monochrome image board (8). In this system, only one monochrome image board was used both to control the LC panel and to take images. The linear stage is moved back to the start position, and the same procedure is repeated with the other filter functions. The speed of the linear stage was 50mm/s and the exposure time was 2 seconds. Intensity in each pixel corresponds to the inner product $W_i^T s$, where W_i is the i-th filter function in the color filter set and s is the spectrum of the object.

Input patterns on the LC panel were determined as follows: Two fixed positions on the panel which correspond to the transmitting central wavelength of 400 nm and 700 nm on the LVF were determined as shown in Fig. 6. The LC panel having 234×382 pixels was controlled by the image board with 512×640 pixels, and the positions of the LC panel were assigned by the pixel number of the image board. In this case, the pixel numbers corresponding to the transmitting central wavelength of 400 nm and 700 nm were 97 and 540, respectively. A designed color filter function was written on the LC panel between the positions of 400 nm and 700 nm by 256-step video signal, and otherwise were at the 0 level. The input level of the direction perpendicular to the wavelength axis was kept constant.

4. Experimental Results and Discussion

4.1 Optical Implementation of Broad-band Color Filters

We first did experiments to implement broad-band color filters. A standard white board of

$BaSO_4$ was placed on the object plane and it was illuminated by a white light source. The purpose of this experiment was just to compare the measured spectra with expected filter functions. Therefore, any kind of white light source having a smoothly varying spectral distribution could have been used. In this experiment we used a halogen lamp. In order to measure spectral intensity of the lamp, 31 intensity images of the standard white board were taken through 31 narrow-band filters ranging 400 to 700 nm at 10-nm intervals. The spectral intensity was determined by averaging the intensity inside the window of 10×10 pixels. Figure 7 shows the spectral intensity of the white light source through the standard white board measured with a CCD camera with narrow-band interference filters. Low intensities in the wavelength range near 400 nm and 650 to 700 nm in Fig. 7 are caused by the low sensitivity of the CCD camera and the low transmittance of the infrared-cut filter attached to the camera.

To know the spectral intensity of the light that passes through the proposed filter system, we conducted the following experiments: A spatial filter pattern that corresponds to a designed color filter function was written on the LC panel. The filter system was operated in order to implement four filter functions in Fig. 2. The resultant intensities through the filter system were taken with the CCD camera through 31 narrow-band filters ranging 400 to 700 nm at 10-nm intervals.

Figure 8 shows the experimental results. Solid lines are the normalized spectral intensity of the light through the implemented filters. Dotted lines are the normalized expected filter functions that are the products between the four color filter functions in Fig. 2 and the spectral intensity of the white light source in Fig. 7. Implemented spectral intensities almost coincided with those expected.

To evaluate the accuracy of this system, we calculated norm errors defined in the following equation:

$$\text{norm error}(\%) \equiv \| P(\lambda) - O(\lambda) \| \times 100$$
$$= \sqrt{(P(400) - O(400))^2 + (P(410) - O(410))^2 + \ldots\ldots + (P(700) - O(700))^2} \times 100, \qquad (2)$$

where $P(\lambda)$ is the normalized expected filter function and $O(\lambda)$ is the normalized spectral intensity of the light through the implemented filters depending on the wavelength λ. Calculated results are shown in Table 1. Averaged norm error was about 5.4%. The results show that the proposed filter system works well and the implemented color filters have sufficient accuracy.

4.2 Spectral Estimation

The proposed system was applied to estimate spectra of natural objects in a two-dimensional image. In an object scene to be examined, test samples were selected from objects whose colors covered the color space widely: a strawberry and a kumquat (a kind of orange) which were placed in front of four colored panels of, left to right, painted blue, painted green, glossy yellow, and glossy red. The four colored panels were the same as used in our previous study.[20] A gray-level image of the object scene is shown in Fig. 9 which was taken in the proposed system under a transparent condition where the input level to the LC panel was set to 255. The size of the image is 241×271 pixels. In Fig. 9, we recognize noisy patterns on the strawberry in which arrays of specularly reflected spots appear. They are diffraction patterns induced by electrodes whose structure is a matrix on the LC panel.

Figure 10 shows four intensity images of the scene, which were taken in our system through the four implemented color filters, respectively. From a set of the four intensity images, a spectrum in the two-dimensional image was estimated for each pixel on the wavelength range of 400 to 700 nm at 10-nm intervals using a pseudoinverse matrix in Eq. (1). The estimated spectrum in the two-dimensional image was compared with that measured by the conventional multispectral imaging method. For this purpose, 31 intensity images of the test scene were taken through 31 narrow-band filters ranging 400 to 700 nm at 10-nm intervals under the transparent condition of the system where the overall input level to the LC panel was set to 255.

Figure 11 shows six results of the spectra at different locations in the scene. Solid lines are estimated spectra from a set of the four intensity images obtained in the proposed system, and dotted lines are spectra measured by the multispectral method with 31 narrow-band filters. The upper three graphs show, left to right, the results of the painted blue panel, the painted green panel, and the glossy yellow panel. The lower three graphs show, left to right, the glossy red panel, the strawberry, and the kumquat.

In the estimated spectra, peak wavelengths almost coincide with those obtained by the multispectral method. However, the estimated spectra fluctuated widely and had unreasonable negative elements in some parts. Errors are believed to be caused by the problem of near singularity that was discussed in our previous work.[20)]

In this spectral estimation using a set of low-dimensional intensity images, the amount of data that we handle decreases considerably. Therefore, the processing of copious image data is not required. The method is also convenient for storing and transmitting the spectral image.

5. Conclusions

We proposed a rewritable transparent broad-band color filter system. The system realizes optical broad-band color filters whose transmitting wavelengths are rewritten arbitrarily. The accuracy of the spectral intensity of the light through the implemented filters by this system was the same or higher than that of the spectral intensity of synthesized lights which were implemented by the spectral synthesizer in Ref. 20.

The proposed filter system implemented color filters with sufficient accuracy, although we cannot say that the results of the spectral estimation in Section 4.2 gave us satisfaction. We believe that the error for spectral estimation was caused by the calculation of a pseudoinverse matrix that includes the problem of near singularity. One possibility to overcome the problem could be use of the Wiener method[3,5] for spectral estimation.

There are more suitable applications of the proposed system, for example, intelligent spectral classification and spectral based parameter estimation.[32] For these applications, a precise spectral estimate is not always required. We can easily understand that the system is a kind of intelligent eye that has many types of photoreceptors. The spectral sensitivity of the photoreceptors can be changed according to our purposes. In this case, a spectral database for filter design should be selected according to objective color samples. It is easy to calculate new filters by the unsupervised neural network.

Acknowledgements

This study was supported by a Grant-in-Aid (No.10555013) for Science Research from the Ministry of Education, Science, Sports and Culture, Japan. The Munsell spectral database is available at the www server of the University of Joensuu, Finland, http://cs.joensuu.fi/~spectral/.

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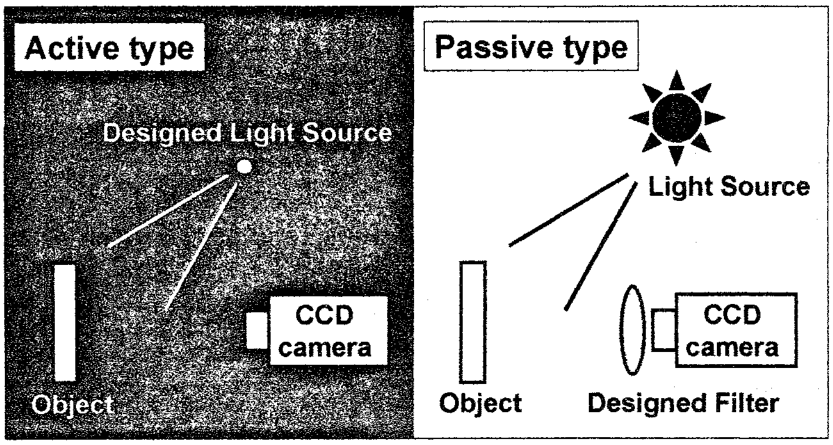

(a) (b)

Fig. 1. Two ways to obtain inner products optically between a spectrum of an object and computationally designed broad-band color filter functions: (a) active type (b) passive type.

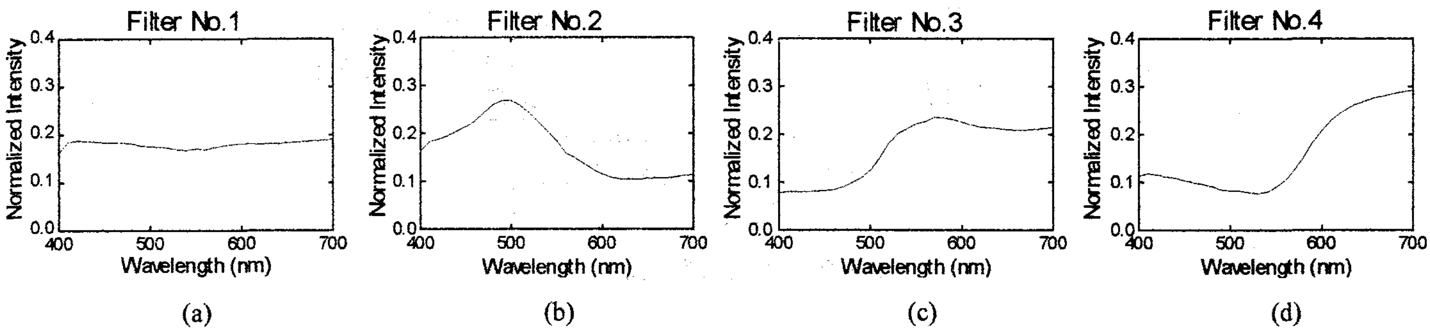

Fig. 2. A set of four color filters designed over the unsupervised neural network.

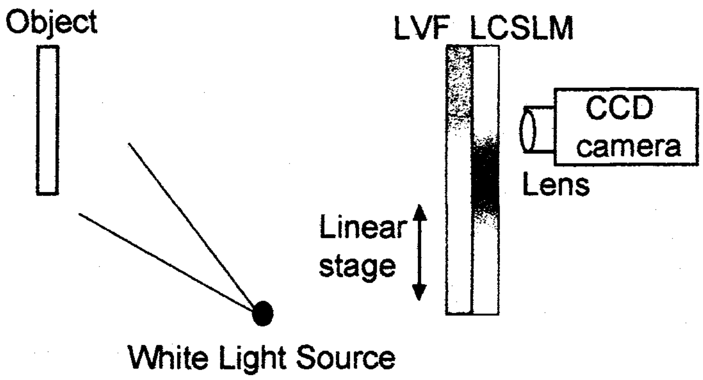

Fig. 3. Experimental setup.

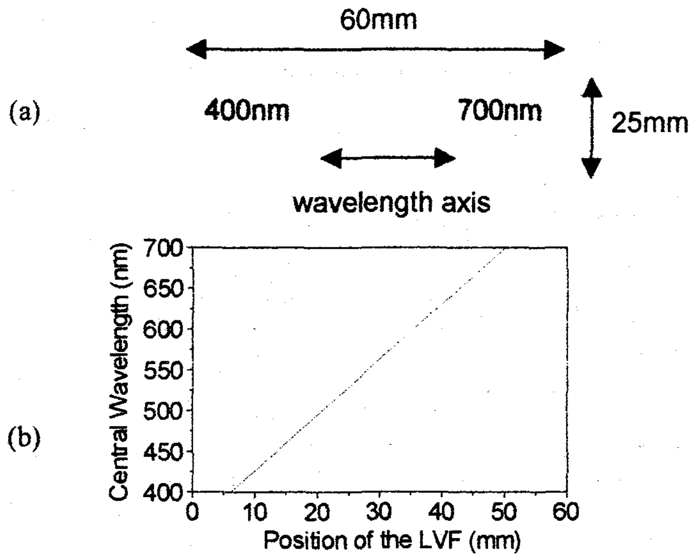

Fig. 4. (a) The shape and (b) the characteristics of the linear variable filter (LVF). The central wavelength of transmitting light varies 400 nm (on the left side) to 700 nm (on the right side) depending on the horizontal axis. The vertical axis is uniform.

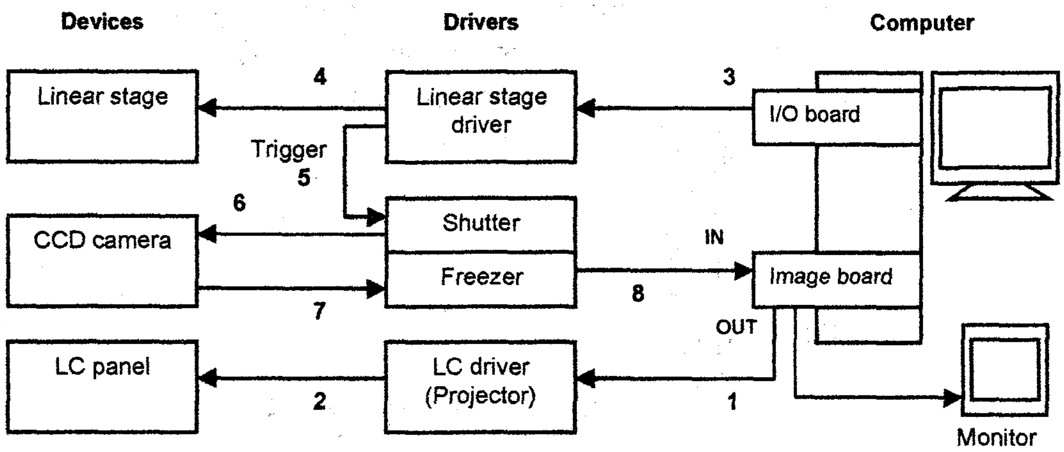

Fig. 5. A block diagram of the control system for the rewritable broad-band color filter system with the numbers in operating order.

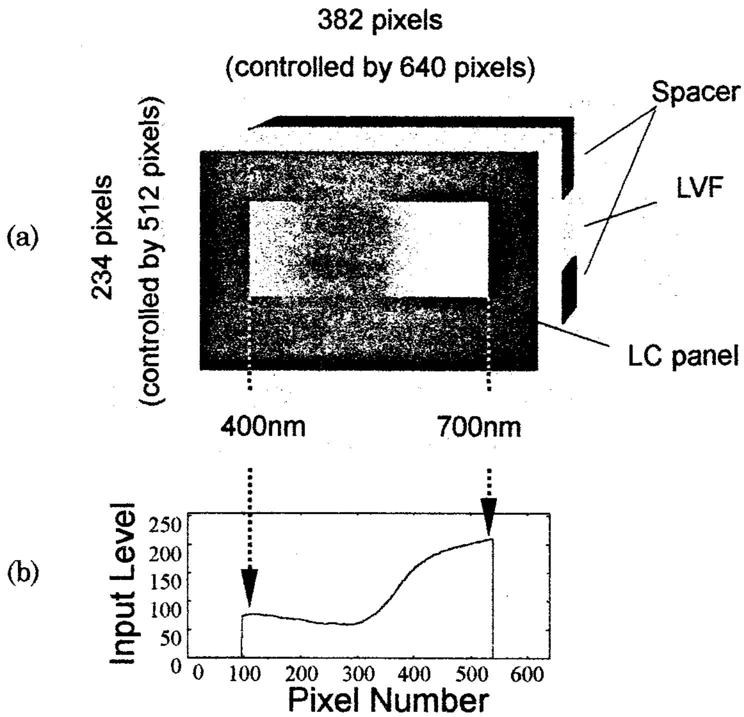

Fig. 6. (a) The combined filter in which a spatial filter pattern is written on the LC panel between the positions of 400 nm and 700 nm of the LVF along the wavelength axis. (b) An input pattern on the LC panel.

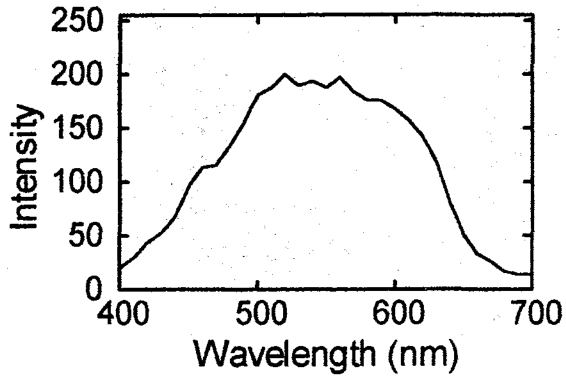

Fig. 7. The spectral intensity of the white light source.

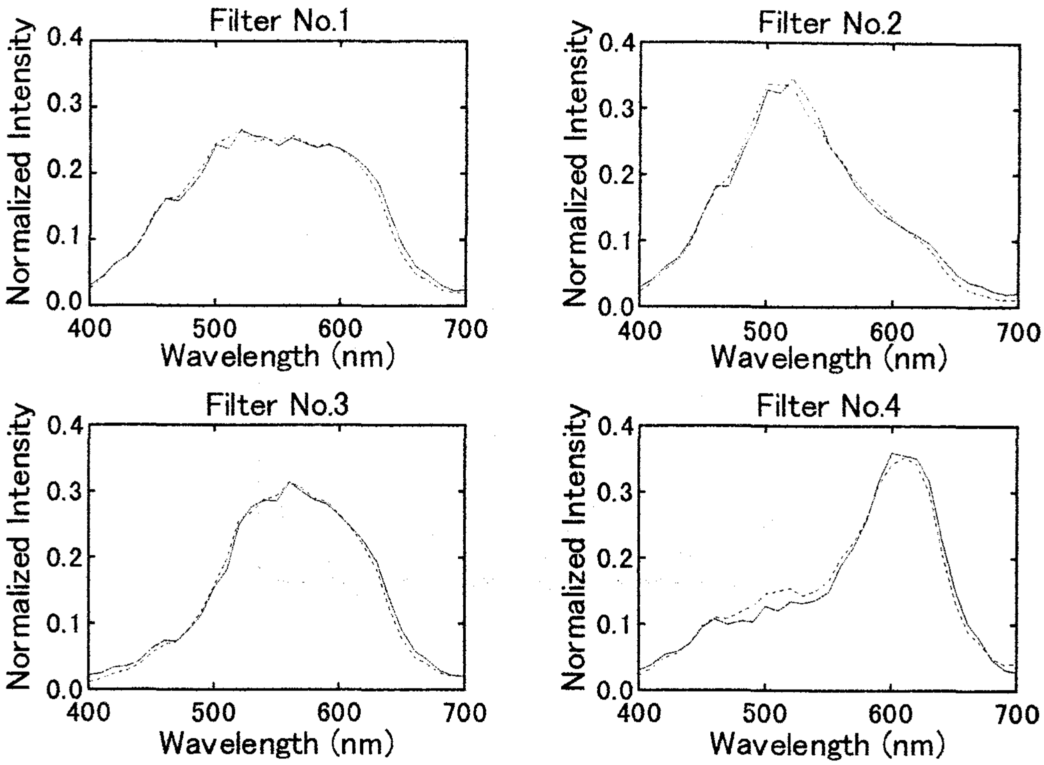

Fig. 8. Experimental results. Solid lines: the normalized spectral intensity of the light through the optically implemented filters. Dotted lines: the normalized expected filter functions that are the products between the four color filter functions and the spectral intensity of the white light source.

Fig. 9. Test samples.

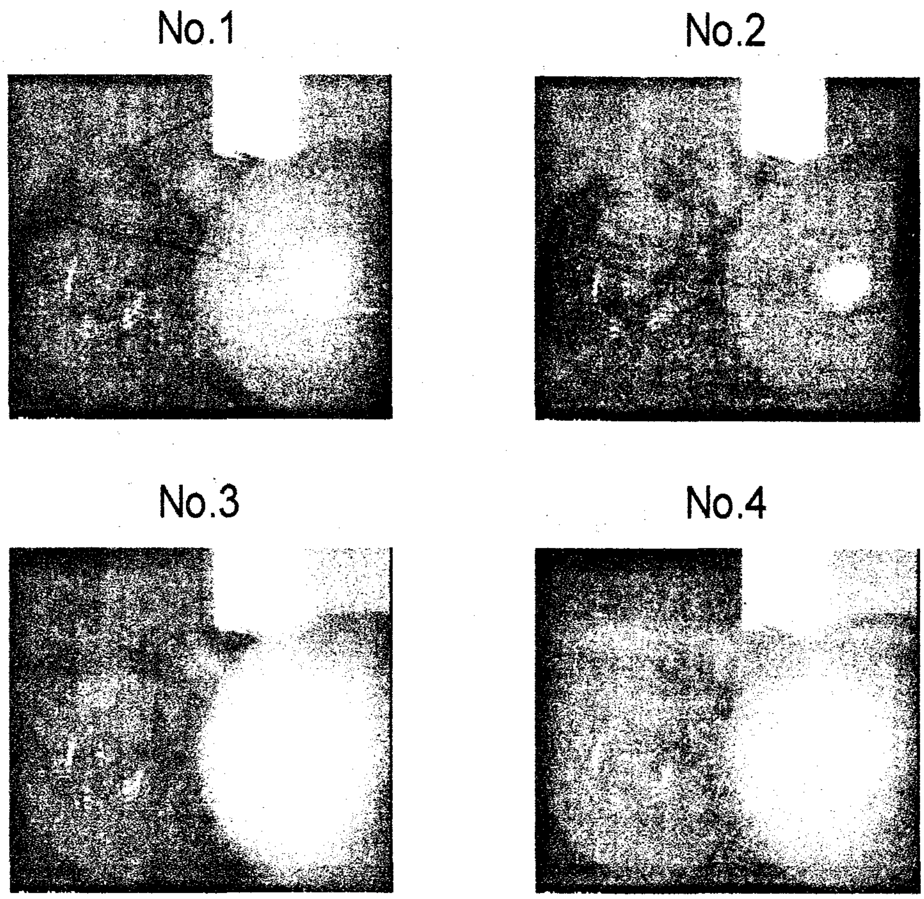

Fig. 10. Four intensity images of the test scene taken by the proposed system through the four implemented color filters, respectively.

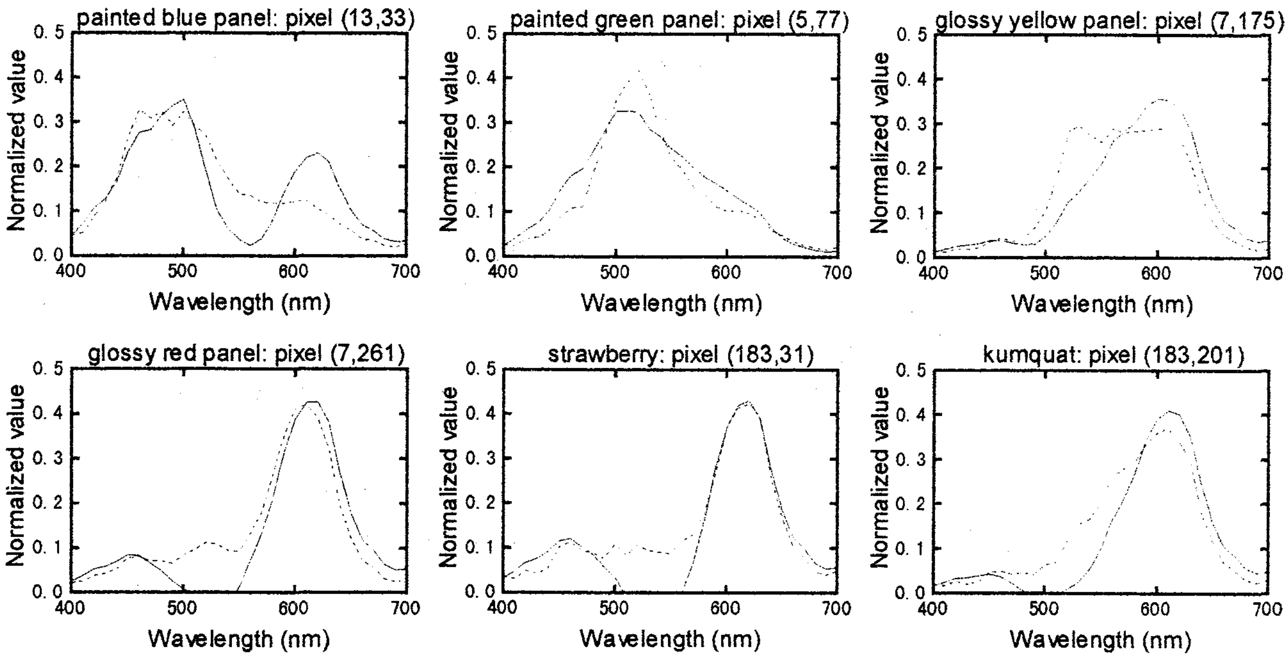

Fig. 11. Six results of the spectra at different locations in the scene. Solid lines: the estimated spectra from four intensity images obtained in the proposed system. Dotted lines: the measured spectra with 31 narrow-band filters.

Table 1. Norm errors over four samples for the normalized expected filters and the normalized spectral intensities of the light through the implemented filters.

Sample number	Norm error (%)
1	4.38
2	5.55
3	4.23
4	7.29
Average	5.36