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論　文　要　旨（博士）

論文題目	分光画像計測技術による食品検査・評価手法に関する研究

（要旨　1,200字程度）

我々は視覚を通して、対象の大きさ、形状、距離や動きに加え、分光情報を色として知覚することで、対象の様々な性質に関する情報を得ている。しかし、我々の視覚系で捉えることが出来るのは、380～780nm の波長範囲にある可視光に限られる。さらに、無限次元である連続したスペクトル情報は、網膜上の L、M、S 錐体によって僅か 3 次元の情報にまで圧縮した上で知覚されており、波長分解能には大きな制限がある。

一方、いわゆる分光計測ではこのような制限を受けない。今日では、様々な波長帯に感度を持つ撮像素子と、数 nm 単位の波長分解能を持つ分光デバイスを用いた分光画像計測により、ヒトの視覚能力をはるかに超越した、膨大な情報を得ることが可能となっている。分光画像計測手法では、非破壊・非接触での計測が可能であり、含有する成分等の化学的な情報が瞬時に得られること、その分布状態を可視化できることなど、他の分析法には無い数多くの利点がある。こういった利点を活かし、特に非破壊計測やリモートセンシングの分野では、他に代替手法の無い強力なツールとして、広く研究が行われている。

しかしながら、分光画像計測法を実応用する上では、いくつかの問題点がある。第一に分光デバイスが高コストである点、第二に波長方向の走査が必要なため、計測時間が長い点、第三にデータ量が膨大であり、計算資源を大量に消費する点が挙げられる。

本論文では、これらの問題を解決するアプローチとして、LED 光源の分光特性を利用する手法と、透過特性を設計した光学フィルタを用いる手法を提案する。いずれも分光情報を用いることで、抽出したい情報に特化した計測システムの特性(LED 光源/光学フィルタの透過特性)を選択/設計するものである。本手法は、分光計測で得られた数百次元の分光情報の圧縮・次元削減を、LED や光学フィルタなどのハードウェアによって実装することに相当する。従って、システムの設計段階では分光計測を必要とするものの、設計したシステムを利用する段階では、高コストな分光デバイスは不要となり、同時に、計測時間や計算資源の問題も解消する。

本論文では、食品の安全や品質の評価に関わる分野への応用を例として、微生物の迅速検出と、牛肉の品質上重要な含有成分である、脂肪と脂肪酸の分布可視化を具体的なターゲットに据え、実用を強く意識した計測・解析手法の開発を行った。また、実用時の使用状況に近い計測システムを試作し、実計測を行うことで、提案手法の実用性と有用性を示した。本論文では、膨大な分光情報をベースに、シンプルで実用的な計測システムを具現化した実例を示したが、同様のアプローチは、波長帯を問わず、分光画像計測手法が有効なあらゆる応用分野への適用が可能と考える。本研究がこれまでの研究用途から実用技術への橋渡しを行い、応用用途を拡大することで、今後の計測技術の発展に大いに寄与できるものと期待する。

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A b s t r a c t

Title	Spectral imaging technique for inspection and quality evaluation of food

(800 words)

When we see an object through our vision, we can recognize the size, shape, distance or motion but also the various properties from its color. The color reflects the spectral distribution about the object. However, there are some limitations on wavelength range and resolution of wavelength in human vision. The "visible wavelengths" of the electromagnetic spectrum is limited to about 380 to 780 nm, and a color is perceived from only three dimensional signals, which is compressed from spectra of infinite dimensional signals by three types of color sensors (L, M, S cones) on our retina.

In contrast, there are no such limitations on hyperspectral imaging. Nowadays, by using an imaging detector suitable for the targeted wavelength range, and a spectroscopic device with capability to select and scan a transparent wavelength electrically with a few nano-meters resolution, it is possible to acquire vast amounts of information beyond the human vision. The imaging technique is called "hyper-spectral imaging (HSI)". There are many unique advantages of HSI method: it is non-destructive, contactless, and easy to use; it can obtain chemical information instantly with no pre-treatment, and visualize its spatial distribution. It is an essential and powerful tool especially for the field of non-destructive inspection or remote sensing.

However, there are some barriers for practical application of HSI: the high-cost of spectroscopic device, the long measurement time due to the wavelength scanning and the large consumption of computational resources come from large numbers of images. This thesis describes information extraction methods by utilizing the hyper-spectral imaging data, and aims to apply it to the food-related field. In this thesis, two approaches to solve above problems are proposed.

As the first application for evaluation of food safety, a method for the rapid detection of microorganism is developed. First, by using the hyper-spectral imaging, it was shown that colonies with diameters of 100 and 300 μm could be detected and identified, respectively. This method has advantages that it can identify a number of different types of microorganism at a time. It enables us to skip the pure culture phase, which needs long time. However, this method needs hyper-spectral measurement. Thus, next, a simple measurement system using spectral distribution of LED light sources was proposed. On the basis of spectroscopic properties of the colony, medium, and LEDs, an optimal combination of two LED illuminations was selected to maximize the contrast between the colony and medium areas. Then, a time course imaging system was developed using a compact incubator with the two selected LEDs. The time-course changes of *Alicyclobacillus acidocaldarius* and *Escherichia coli* at two different dilution levels were monitored using the system. From the results, a similar growth rate was estimated amongst the same species of microbes, regardless of the dilution level, and the ability to detect a colony of approximately 26 μm in diameter in a detection image was confirmed.

As the second application for evaluation of food quality, the spatial distributions of food constituents were visualized. Concretely, fat and various fatty acid contents in a raw beef cut were predicted and visualized. First, the effectiveness of the spectroscopic approach for this application was confirmed through experiment by a traditional method with hyper-spectral data. After that, this study proposed a more simple and practicable measurement system with equivalent performance to hyper-spectral method, using a set of a few optical filters. The filter shape was a band-pass-filter (BPF), and the band-pass characteristics were specifically designed for each content individually. By comparing the prediction results of actual measurement using a set of three BPFs with hyper-spectral imaging (about 200 wavelengths), the superiority of filter method in the performance was confirmed.

In both applications, the spectral characteristics of LEDs/BPFs are specifically pre-selected/designed for extracting target information from hyperspectral information. These methods are equivalent to reducing the dimensions from hundreds (obtained by hyper-spectral measurement) to a few by hardware using the spectral characteristics of LEDs/BPFs. Therefore, although the hyperspectral measurement is required in the design phase, no spectroscopic device is needed during the application phase. In these methods, only a few images are acquired by switching LEDs/BPFs. It enables us to solve the problems of the cost, measurement time and computational resources at a time. Moreover, a brighter image can be obtained by constraining the minimum bandwidth in the filter design phase. It allows for shorter exposure times, and improves S/N ratio.

Prototype measurement systems with consideration of practical use were developed, and by using them, actual measurement was performed to evaluate the performance. As a result, the practicality and availability of proposed methods were demonstrated. These approaches might be also applicable to various fields where the spectroscopic method can be applied. This study can bridge between research application and practical use, and expand the application area of hyperspectral imaging technique.