氏　　　　　名	MD. ABDUL MANNAN
博士の専攻分野の名称	博士（学術）
学 位 記 号 番 号	博理工甲第 885 号
学位授与年月日	平成 24 年 9 月 14 日
学位授与の条件	学位規則第 4 条第 1 項該当
学 位 論 文 題 目	Material Information Acquisition for Interactive Object Recognition in Service Robots （サービスロボットにおける対話物体認識のための材質情報の獲得）
論 文 審 査 委 員	委員長　教　授　久野　義徳
	委　員　教　授　前川　　仁
	委　員　教　授　島村　徹也
	委　員　准 教 授　小室　　孝

論文の内容の要旨

The identification or recognition of material of real object is a fundamental aspect of noncontact visual perception. Material recognition capability in open eyes helps a person to identify the correct object among various similar types of candidate objects. For example, a person can easily distinguish between paper made cups and ceramic cups in open eyes. By inspired from the human natural capability, material recognition for robot vision application gained our attention. If we want to develop a service robot which will work in home environment by interacting with human users, we need to build its vision system close to the human vision system. In the real world, a person utilizes several attributes to specify a particular object certainly. Consequently, to establish proper interaction between users and robots, robots should have ability to understand and extract those attributes from objects like shape, size, color etc. Here we are particularly interested in object’s material, because it is also often used to specify target objects by users. It could be possible to obtain material information of an object or alternatively its surface’s micropartical size information from the optical signal reflected by its surface. To enhance the discriminating feature among various types of surfaces we use larger wavelength incident light in our proposed method.

Initially we investigate whether the longer wavelength light reflection from object's surface gives information about the surface micro-particle size or material. The amount of light reflected by an object, and how it is reflected, are highly dependent upon the smoothness or texture of the surface. When surface imperfections are smaller than the wavelength of the incident light (as in the case of a mirror), virtually all of the light is reflected equally in a specific direction. However, in the real world, most objects have convoluted surfaces that exhibit a diffuse reflection, with the incident light being reflected in all directions. The light reflects off from surfaces in a predictable manner in accordance with the law of reflection. If the light rays fall upon a smooth surface, then the light rays reflect and remain concentrated in a bundle upon leaving the surface. On the other hand, if the surface is microscopically rough, the light rays reflect and diffuse in many different directions. This research also explores how light waves are reflected by smooth and rough surfaces. The infrared light has wavelength greater than the microscopic surface detail, so that the surface-laser interaction causes diffraction and generates a pattern which is specific to each material surface. This variation is increased by infrared character of laser which penetrates into subsurface and causes diffuse reflection again. This differentiation would not be possible under the shorter wavelength visible light. Our non-contact active vision technique utilizes the local surface geometry of objects and the longer wavelength scattering light reflected from their surface. After investigating the properties of microstructure of the material surface, the system classifies various regular shape household objects into several material categories according to the characteristic of the micro particles that belong to the surface of each object. We use a time-of-flight range sensor for this active vision technique.

However, the material identification from a free-form 3D object is a fundamental problem in computer vision. There are several house hold 3D objects which have very complex shape. In this stage our objective is to estimate 3D free-form real object surface characteristics to identify the material based on surface reflectance analysis. To investigate the surface micro-structural detail, we use a modified Torrence-Sparrow light reflection model. The surface roughness parameter, which represents the microstructure characteristics of object surface and can be an indicator of object material, is determined from the reflection model. We also have demonstrated the feasibility of the method through experiments.

Moreover, we propose another method that analyzes the reflection pattern of infrared light to estimate the object material according to the degree of surface smoothness (or roughness). It measures reflection intensity patterns with respect to surface orientation for various material objects. Then it classifies these patterns by Random Forest (RF) classifier to identify the candidate of material of reflected surface. We demonstrate the efficiency of the method through experiments by using several household objects under normal illuminating condition.

Our previous method needs only a time-of-flight range sensor to identify the material of target object. Although it produced promising results (72% accuracy), the method needed long processing time (average 23 seconds per object) and was able to handle only with homogeneous surface objects such as single color objects. The range data from the 3D range sensor are very noisy. To solve this problem, we used data for a large number of points and applied some complicated smoothing filter to each point of surface. Thus the method needed long processing time. In addition, we assumed that all patches or segments on the object surface have the same color properties. Thus, the method can work only for single color objects. The SwissRanger (ToF range sensor) camera uses infrared light to illuminate the scene and has a visible light elimination filter in front of its CCD array. However, we empirically know that reflection intensity values are smaller for darker objects. We examined this issue experimentally and found that the normalized reflection patterns are similar for the same material whatever their color.

This allows our previous method to recognize objects material regardless of its color if it is a single color and uniform brightness object. However, if it has different color parts, the method cannot work. We have solved these issues and present a modified version of our previous method that can work for multicolor objects in short processing time. Also, in our research we re-modify the Torrance-Sparrow model to represent distant independent surface reflectance patterns. To do so, we have given up our policy of using only the SwissRanger and use a color camera with the range sensor. We set the camera so that we can obtain gray-scale values of corresponding points in the range sensor data. From experiments, we found that the reflection intensity of a point is approximately proportional to the gray level of the point in gray-scale image. Thus, we have devised two methods. One is the normalization method. We normalize IR intensity values by dividing them by the gray levels of corresponding points.

The second is the equal gray-level method. We apply gray-level segmentation to the camera image and choose the largest region (or a set of regions with similar gray scale level whose combined area is largest). We collect the data only from those region(s) for recognition. The normalized method needs the precise positional calibration between the range sensor and the gray-scale camera. In addition, gray levels of the camera cannot be so stable. The equal gray-level method is simple and practical as long as the method can find enough data points. Therefore, we have adopted the same gray-scale method.

Although the SwissRanger has several built-in noise removal scheme, but the data of SwissRanger 3D camera are still noisy. There are two types of noise, saturation noise and random noise. The random noise occurs for all types of surfaces. Although it is hard to eliminate it completely, we input 20 range images for a scene, and filtering them to reduce the saturation noise.

After removing saturation noise, we have 20 almost saturation noise free range images. Then we compute the median at each pixel location for these 20 images to obtain the range image with more reduced random noise. We construct the reflection pattern from this image. In our previous method, we generate surface patches for almost all pixels. However, since the noise is much reduced, we do not need to use a large number of pixel data to estimate the reflection pattern. Here we experimentally determine to use 20 pixels.

To select these 20 pixels, first we cluster all pixels into 20 groups according to the pixel intensity. Then from each group we select the highest intensity pixel. We generate a surface patch from the selected pixels and use their 5x5 neighbors to estimate the reflection pattern.

To perform experiments, we arranged 50 household objects of various sizes, shapes and colors. They included multicolor objects. These objects were divided into 5 material groups (plastic, paper, wood, fabric and ceramic), 10 objects in each group. In our reflection pattern classification experiment, among 50 experimental objects we took 3 objects from each class to train the classifier. When obtaining the reflection patterns in the training stage, we put each object about 40 cm in front of the range camera. We performed recognition experiment 5 times for each rest of the objects for test. Each time we randomly changed the orientation of the target object with respect to the viewing direction. The recognition rate of the method is 71.5% and the total time required by the system to recognize each object is 2 seconds. Our previous method was not able to recognize ceramic because ceramic objects yield a large amount of saturation noise. As we have also devised a saturation noise removal technique, our modified method can identify ceramic. It can also work for multicolor objects. In such harder conditions, the modified system can show almost equivalent recognition results compared to the results of the initial approach in simple conditions. Although the figure itself may not be so high, the recognition rate of the method is reasonable because surface roughness of objects actually varies much even for the same material objects. However, this level of recognition can be useful in the interactive object recognition framework. In addition, the processing time has been much reduced. Since we input 20 images by the sensor to reduce noise, we need at least about a second to input them. We need to improve the sensor to further reduce the recognition time.

We are now working on an interactive robot vision system in which the robot uses this material recognition method to respond users' utterances referring to material. Although we will work to further shorten the processing time, the current level of processing time may not be a major problem in this application, since the robot can execute this process background before actual interaction about material.

As the final improvement, we propose and implement an integration technique of other features like shape and color with the near-infrared reflection pattern. Experimental results (79% accuracy) show that our system performs material recognition reasonably well, outperforming our previous material recognition systems.

We demonstrate the efficiency of this method through several experiments utilizing 50 house hold objects including single and multi color objects in uncontrolled lighting condition.

Our main objective of this research work is to introduce material information about house hold objects along with color, shape, and other attributes in order to more efficiently recognize target objects in the interactive object recognition framework. In this research, we first proposed a basic method of recognizing object material by using a time-of-flight range sensor. Then, we modified the method to work for various objects in less processing time. We implemented the method on a robot to develop an interactive object recognition system. Experimental results using the robot system proved the usefulness of the method. The proposed method can be an important techqnique in developing home service robots.

論文の審査結果の要旨

当論文審査委員会は、当該論文の発表会を平成 24 年 7 月 11 日に公開で開催し、詳細な質問を行い論文内容の審査を行った。その論文発表を含む学位論文の審査の結果、本提出論文を博士（学術）の学位論文として合格と判定した。以下に審査結果の要約を示す。

本提出論文はコンピュータビジョンの分野における物体認識に関するものである。物体認識の研究は、近年、頑健な局所特徴量と機械学習の利用によって進展してきているが、まだ、どのような状況でも確実に認識できるものはない。申請者の研究室では、物体認識の応用として、身体の不自由な人に頼まれたものを見つけて取ってくるサービスロボットを開発している。この場合、物体が認識できなければ、依頼を実行できない。そこで、自動物体認識に失敗した場合に、対象物体についての情報を対話で依頼者に聞き、それを利用して物体を認識する対話物体認識を検討している。これまでに比較的、画像から直接的に得られる色などについて検討したが、本論文は、物体の材質情報をコンピュータビジョンにより求める方法を提案するものである。これまでにも材質の推定を行う研究はあったが、それらでは特殊な光学系が必要であったりして、サービスロボットに簡便に使えるものではなかった。本論文は、この問題を解決するもので、ロボットによく使われる TOF(time-of-flight) 方式のレーザレンジファインダを利用することでサービスロボットに使用できる材質推定法を提案している。

本論文は 7 章からなるが、まず、第 1 章では、上述のような研究の背景と目的を述べている。

第 2 章では、提案する材質推定法の基本的な方法について述べている。TOF 方式のレーザレンジファインダは近赤外レーザ光を投射し、反射して戻ってくるまでの時間から物体までの距離を求めるが、その距離データとともに、反射光の強度もセンサ出力として得られる。提案の材質推定法では、まず、距離データから物体上の各点の面の向きを求め、そこからセンサから見たその点の向きを求め、その点からの反射光強度と組合わせたデータを得る。このセンサでは、センサ部分から近赤外光を投射するので、このデータは光源の方向から面の向きがずれると、どのように反射光が減衰するかを示すことになる。滑らかな物体では、面の向きがずれると急減に反射光は減衰するが、粗い物体では、減衰の程度が小さい。これは物体の材質を直接的に示すものではないが、紙、プラスチック、木、陶器などの材質により、減衰パターンに違いが出る。提案手法の基本原理は、このパターンを求めて識別することである。この章では、平面や円筒など簡単な幾何形状部分をもつ物体に対して識別する方法を示している。

第 3 章では、任意の形状の物体に対して認識ができるように手法を拡張している。この場合、物体の各点の面の向きを正確に求める必要がある。そこで、レンジファインダーの計測結果からノイズをフィルタにより減少させるとともに、面の向きの計測に適した局所的に平面に近い部分を選択して利用する方法を考案している。

第 4 章では、実際に多くの物体を学習データとして識別器を構成し、それを用いて認識の実験を行っている。

提案の方法は対象物の表面が同質であることを仮定している。しかし、実際の物体では、色の違う部分があったりする。第 5 章では、この問題に対処するために、レンジファインダの他にカラーカメラを用い、同じ色の部分だけを用いて、材質を推定する方法を提案している。また、処理を高速化するために、推定に必要なデータ数をしぼる改良も行っている。

第 6 章では、さらに他の画像特徴も利用することで認識精度を向上させることを検討している。そして、最後に実際にロボットにシステムを実装して対話物体認識の実験を行っている。プラスチック、木、紙、繊維、陶器の 5 つの材質に対して、認識率は全体で 72%程度であった。対話物体認識に使用する場合は、他の属性により候補物体が限定され、その中で、ユーザに指示された材質の物体を検出できればよい。実際に

ロボットシステムで実験した結果、対話を通じて色や形が同一で材質だけが違う物体について、識別が可能であることが示された。

最後に第７章で、論文の内容をまとめ、今後に残された課題を議論している。

以上のように、本論文の内容は、学術的に意義のある研究であると評価できる。よって、当学位論文審査委員会は、本論文を博士（学術）の学位論文として合格と判定した。