主 論 文 の 要 約

論文題目

A Study of Vision-based Tactile Sensors Based on Deformation Analysis of Elastic Bodies for Dexterous Handling of Robots

（ロボットの器用な把持操作のための弾性体の変形解析に基づく光学式触覚センサの研究）

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論 文 内 容 の 要 約

Tactile sensing is a key point to enable robots to imitate skilled human behaviors because humans can easily control their muscles by feeding back multimodal tactile information. The purpose of this study is to develop a tactile sensor allowing multimodal sensing with a simple and deformable structure. A vision-based tactile sensor is proposed that can obtain multimodal tactile information including the contact force, degree of slippage, shape, contact region, and location of an object.

Chapter 1, Introduction, presents the background, previous work, problems and purpose of this paper. Among various types of tactile information, the focus is on five types of tactile information, which are the multi-axis contact force, slippage, shape, contact region and location (position and orientation) of an object. This chapter also describes each of these tactile information sources. Many researchers have developed various types of sensors to obtain tactile information based on electrical resistance, capacitance, piezoelectricity, electromagnetic components, ultrasonic sound, optical components and so on. This chapter also introduces a number of previously developed sensors, presented according to the sensing principle. This chapter finally suggests the problems with the previous sensors and enumerate the requirements of tactile sensors, considering the sensors introduced in the preceding sections. In order to achieve multifunctional and dexterous robots in consideration of practical applications, the suggested requirements should be satisfied.

Chapter 2, Vision-based Tactile Sensor, introduces the vision-based tactile sensor for acquiring tactile information which consists of a charge-coupled device (CCD) camera, LED lights, a deformable touchpad and so on. This chapter also mentions two types of the touchpads: one is a transparent elastic touchpad, and the other is a semitransparent fluid-type touchpad. The surface of the touchpad is made of an elastic membrane constructed of silicon rubber. The inside of the membrane is filled with translucent, red-colored water. A dotted pattern is printed on the inside of the touchpad surface for observation of the touchpad deformation. Analysis of the deformation yields multimodal information when the touchpad is deformed by contact with objects, using an image of the inside of the deformed touchpad captured by the CCD camera.

Chapter 3, Strategy and Fundamental Theory for Multimodal Sensing, presents the strategy for multimodal tactile sensing using vision-based deformable sensors, comparing it with the mechanism of human skin based on knowledge on human skin. The strategy for multimodal tactile sensing using the proposed sensor is divided into two steps. In the first step, calculation of the three-dimensional shape of the touchpad is attempted using the fluid-type touchpad. In the second step, calculation of other tactile information is attempted from the three-dimensional shape and dot pattern.

Chapter 4, Estimation of Slippage Degree, proposes a new method for estimating the slippage degree based on the adaptive selection of the reference image and compensation for the displacements of dots. The reference image is selected based on the three rules. The first rule is selecting a recent captured image as the reference image as much as possible. The second rule is updating the reference image such that the difference between the reference and current images is larger than a threshold. The third rule is selecting the reference image from among the images that are captured after the change of the moving direction. Chapter 4 proposes an extension to make it possible to use this method under dynamically complex but general situations, as follows. First, the contact surface deforms after macroscopic slippage occurs or the slippage direction is changed. Second, the contact surface rotates with an applied moment. Third, the captured image is locally zoomed with a significant change in grip force.

Chapter 5, Estimation of Shape of Objects, proposes a new method using the fluid-type touchpad for estimating the shapes of the touchpad and object. Intensities of red, green, and blue bands of the light traveling in the touchpad are analyzed in this chapter in order to estimate the shape/irregularity of the object. The LED light traveling in the touchpad is scattered and absorbed by the red pigment in the fluid. The depth of the touchpad is estimated by using the intensity of the light obtained from the red-green-blue (RGB) values of the image, in consideration of the scattering and reflection effects. The proposed method for estimating the shape of the touchpad is divided into some parts. The method firstly formulates this relationship based on the fundamental theory. Next, the reflection coefficient depending on the shape of the membrane is eliminated in the proposed formulation by using the two channel values of the pixel. Besides, the method eliminates the unknown constant parameters by using the initial values of the touchpad shape and the RGB values of the image which can be obtained in advance. Next, the method identifies the constant parameters. Although the three-dimensional shape of the touchpad is calculated, the obtained shape is compensated for decreasing the estimation error of the shape. Next, this chapter proposes the filter to smooth the calculated shape, where smoothing the touchpad shape is useful for sensing other tactile information using the touchpad shape. Next, the method calculates shape of the object from the outer shape of the touchpad. Finally, this chapter considers the relationship between the measurement accuracy of the proposed method and the RGB channels of the image.

Chapter 6, Estimation of Contact Region between Sensor and Objects, proposes a new method using the fluid-type touchpad for estimating the contact region between the touchpad and an object, firstly considering the relation between the shape of the sensor surface and the contact region. The necessary and sufficient condition is formulated for a certain point to belong to the contact region; this uses only the curvature radiuses in various directions for small segments on the sensor surface. The curvature radiuses of the touchpad are geometrically calculated. Finally, the equation evaluating the contact region based on the curvature radius is adjusted to compensate for errors of the calculated curvature radius.

Chapter 7, Estimation of Position and Orientation of Object, proposes a new method using the fluid-type touchpad for estimating the position and orientation of an object. Defining a contact reference dot yields the positions and orientation of the contacted object. The translational movement of the object is equal to the three-dimensional movement of the contact reference dot when the object does not rotate. The orientation of the contact reference dot is equal to that of the object based on three basis vectors around the contact reference dot. Finally, in order to calculate the rotation angle of a rolling object, the contact reference dot is continuously detected, and the orientations of the contact reference dots are integrated.

Chapter 8, Measurement of Multi-Axis Contact Force, proposes a new method using the fluid-type touchpad for measuring multi-axis contact force. Multi-axis contact force is formulated from the elastic membrane tensional force on the touchpad surface and the touchpad inner pressure measured by a pressure transducer. The tensional force is obtained by solving the equilibrium equations of the compartmentalized segments of the membrane with the boundary conditions. The calculation method of the tensional force is divided into the five steps. In Step 1, the method compartmentalizes the entire membrane into a number of segments with the sufficiently small size. Next, the method develops the equilibrium equations of each segment in consideration of the tensional forces and the inner pressure in Step 2. Here, the boundary conditions for obtaining the tensional force are the key points. In Step 3 and Step 4, the method obtains the boundary conditions. In concrete terms, the method estimates the directions of the tensional forces at the border of the membrane based on the side dots printed on the side of the inner membrane and obtain the magnitude of the tensional forces at the border of the membrane by considering the developed equations under the specific contact condition. In final step, the method calculates the tensional forces at the border by solving the equations with the boundary conditions by the iteration method like the Gauss-Seidel method. The proposed method is general and can be applied to various touchpad contact situations.

Chapter 9, Experimental Results, validates the proposed methods for acquiring multimodal tactile information through experimental results. One of the advantage of the proposed sensor is that the sensor can many types of tactile information simultaneously. This chapter also shows that simultaneous acquisition of the tactile information is successfully applied. Comparisons with other previous methods are also made to confirm superiority of the proposed methods.

Chapter 10, Conclusion, summarizes the contribution of this paper. The relationships between the sensing methods and introduced assumptions for an object are mentioned; this is helpful in applying the sensor. Finally, we consider the open problems that still remain and future prospects.