GelForce: A Traction Field Tactile Sensor for Rich Human-Computer Interaction

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ABSTRACT

Recent advances in vision-based tactile sensation have given rise to a novel class of high-performance sensing devices that measure traction fields (i.e. distributions of 3-D force vectors) with density comparable to the biological sense of touch. While this has been an emerging trend in robotics, it introduces diverse new possibilities for human-computer interaction as well. We describe how to apply computer vision techniques to measure the traction field applied to the surface of a silicone body, and discuss the potential of using the computed vector distribution as a rich and versatile interface for interactive desktop applications.

Keywords: vision-based tactile sensing, force vector field user interface, vector field visualization

1 INTRODUCTION

The specific objectives for researchers in data visualization and robotics are generally distinct, but not divergent: they share the fundamental goal of establishing technology in which people can interact with machines as if they are handling natural objects, in a cybernetic way that is truly human-oriented. Combining their respective innovations would be of mutual benefit and may also introduce new possibilities to the domain of human-computer interaction. In this spirit, we propose a practical application of a tactile sensor that measures a field of force vectors as an intuitive computer interface with a rich geometrical structure.

The distinctive feature of the tactile sense over the other senses is its integral relationship with our bodily movement. We are generally unaware of this until we lose sensation through anesthesia or loss of blood flow. Simple tasks like grasping an egg become critically impaired without the interplay between muscle contraction and mechanoreceptors in the skin. In particular, the weight of an object is felt not only by contraction of the muscle but also force parallel to the skin. Fragile objects are grasped safely by adjusting the proportion of perpendicular and parallel force. This aspect has been studied extensively in the robotics literature [1][2][3], and a variety of miniaturized tactile sensors have been developed to endow mechanical hands with the capability to perform fine manipulation tasks.

However, to our knowledge there have been few or no efforts to introduce traction field sensors into the forum of interactive desktop applications. We suspect two reasons for this, the first being the projected complexity and cost of manufacturing a miniaturized, high-performance sensor that can measure force vectors with high density. Perhaps the second reason is that it is still unclear what advantage this class of sensor would have over established sensors such as force feedback devices that measure a force vector at a localized point [4], or piezoelectric element devices that measure dense distributions of force magnitudes [5]. We shall address both concerns in this paper by introducing a method to measure force applied to the surface of a silicone body using computer-vision techniques, and presenting the novel capabilities of this sensor through interactive digital art.

2 VISION-BASED TACTILE SENSING

The proposed sensor has a relatively simple system design, consisting of a transparent silicone elastic body, and a video camera placed underneath the body to measure the internal deformation according to force applied from humans or other external sources (see Figure 1).

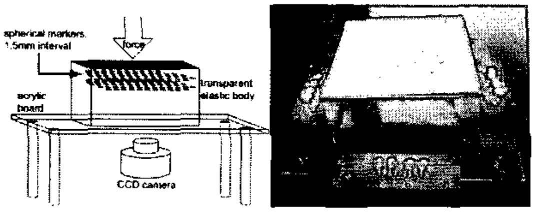

Figure 1: Desktop style vision-based force sensor composed of rectangular transparent silicone body.

2.1 Derivation of Force from Elastic Displacement

2.1.1 Elasticity Theory

Perhaps the most scrutinized problem in elasticity theory is the derivation of deformation of an elastic body given an applied stress. If we assume the elastic medium is linear, isotropic, and homogeneous, the linear relation between three-dimensional stress $\vec{\varepsilon} = \{\varepsilon_x, \varepsilon_y, \varepsilon_z\}$ and strain $\vec{\sigma} = \{\sigma_x, \sigma_y, \sigma_z\}$ is expressed through Hooke's law [6] as:

$$\begin{aligned}\varepsilon_x &= \frac{1}{E}\left[\sigma_x - \nu(\sigma_y + \sigma_z)\right] \\ \varepsilon_y &= \frac{1}{E}\left[\sigma_y - \nu(\sigma_x + \sigma_z)\right] \\ \varepsilon_z &= \frac{1}{E}\left[\sigma_z - \nu(\sigma_x + \sigma_y)\right]\end{aligned} \tag{1}$$

where E is Young's modulus characterizing the stiffness of the material, and ν is Poisson's Ratio characterizing the compressibility of the material. This fundamental relationship can reframed for a continuous elastic medium as a convolution to relate the internal

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deformation of the elastic body to the distribution of external force applied at the surface, also known as a traction field. Expressing this convolution in matrix form, we may derive force from deformation by solving the inverse problem. Please refer to [7] for details.

2.2 Measuring Elastic Deformation

There are a myriad of techniques to measure visual displacement [8], with a general tradeoff between speed, accuracy and robustness. Fortunately, tracking the deformation of a stiff, energy-conservative silicone body is a highly specific problem with considerable geometrical constraints, which may be exploited to develop a specialized method with both high speed and accuracy. The proposed sensor uses a CCD camera placed beneath the transparent elastic body to track interior points distinctly indicated by circular markers. Using a center-of-mass calculation, a displacement distribution of the markers is tracked to sub-pixel accuracy, with a precision of approximately 40 μm.

Although a single camera can only obtain 2D information, by aligning different colored markers at separate depths within the silicone body, we obtain 3D information by their corresponding differences in displacement resulting from the applied force. Through a linear least squares method, the traction field may be computed quickly with a matrix-vector multiplication using the precomputed convolution matrix.

3 APPLICATIONS, PRESENT AND FUTURE

A major design criterion for this sensor is to serve as an affordable traction field input device for commodity PC systems. It is critical to achieve a high density of sensing to appeal to the human senses, and with a high refresh rate to realize the concept of "What-You-See-Is-What-You-Touch".

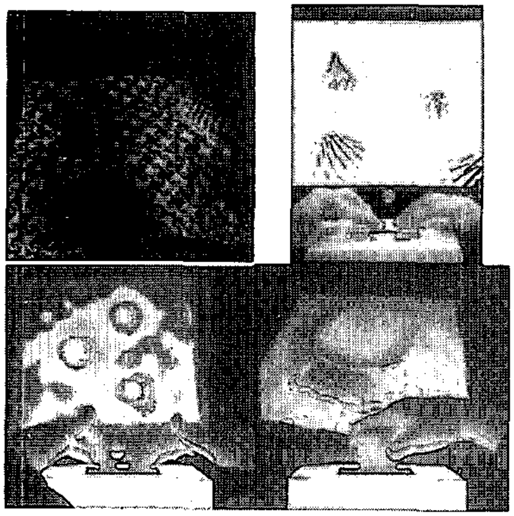

Figure 2: Applying a force vector field tactile sensor to achieve sophisticated visual effects

The developed sensor has proven to be exceptionally adept at measuring qualitative information unobtainable by existing sensors, so it is a rather promising tool for a host of applications in visualization, as well as tract analysis applications in sports, industry, and medicine. It can function as an intuitive computer interface like the touchpad or mouse, except with much more structure. This characteristic provides lush input for real-time physical simulations. It also makes it a powerful means to interact with virtual environments modeled with physical parameters. We envision accompanying the tactile sensor with more conventional input devices such as a mouse or trackball in order to adaptively apply real-time traction field input to familiar interactive applications such as image processing, CAD design, image processing, sound synthesis, and computer entertainment (Figure 2).

It is no exaggeration to say that every scientific technology is based on sensors. For example, audio recording cannot exist without the measurement of sound, and television broadcasts would be impossible without catching radio waves as picture signals. Just as the video camera and microphone adeptly measure information for visual and acoustic sensation, we believe the core technology of the developed sensor has great potential to develop mainstream devices to enhance our daily lives. The first reason is that the sensor can measure complete information about force, that is direction, magnitude and distribution, with the same versatility as the human tactile sense. Second, its sensing mechanism is simple, so the sensor can adapt various shapes and be manufactured cheaply. Finally, powerful and intuitive input devices will surely be needed to accommodate emerging markets related to continual improvements in processing power.

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