Three-Dimensional Force Sensor based on Deep Learning

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Abstract. Human skin can accurately sense subtle changes of both normal and shear forces. However, tactile sensors applied to robots are challenging in decoupling 3D forces due to the inability to develop adaptive models for complex soft materials. Therefore, a new soft tactile sensor has been designed in this paper to detect shear and normal forces, including a soft probe and image acquisition device. First, to capture the deformation of the sensor, colored silicone squares were embedded in the soft probe. Capcamera movement of the colored squares under external forces. The image dataset collected at different 3D forces is then input into a deep learning model. Finally, a custom miniature image device is acquired and embedded in the soft probe to miniaturize the sensor. Computing results obtained from experimental datasets show that the proposed method can accurately decouple the 3D forces. Robots can grap vulnerable objects with sensors prepared at the robot's tip. The tactile sensors studied in this paper are expected to be applied in robotics fields such as adaptive grasping, dexterous manipulation and human-computer interaction.

Keywords: Tactile sensing · Robot technology · Deep learning.

1 Introduction

Human skin contains four mechanoreceptors (SA-I, SA-II, RA-I, RA-II), allowing humans to perceive subtle changes in force during contact with objects accurately [1,2]. Moreover, force perception is a natural appeal to barriers to visual

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perception [3]. However, when a robot has visual perception impairment, such as insufficient light supply and occlusion, in complex tactile contact task scenarios such as robot dexterous operation, good tactile feedback (such as contact force) can provide rich proprioception, resulting in more reliable operation and control strategies [4]. Therefore, designing soft force sensors like human skin is critical to the robot field, which can promote robot development.

The traditional soft mechanical sensor generally detects the force signal through the change of capacitor [5,6], resistance [7,8] and other electrical signals caused by the deformation under the action of external force. However, with the development of vision algorithms, visual and tactile sensors have emerged, which model the contact colloidal deformation information captured by the camera as tactile information such as force signals through visual algorithms. With the advantages of high spatial resolution, low cost and rich tactile information, it has gradually become the hot spot direction of tactile sensors [9].

The design of vision-tactile sensors comprises the colloidal contact layer, light source structure and camera imaging system. In MIT Gelsight's visual-tactile sensor [10], they introduced labeled points on the reflective film inside the soft elastomer to capture the displacement of labelled points under 3 D forces and established the mapping relationship between the labelled point displacement and 3 D forces through finite element analysis to realize 3 D force detection in the soft environment. The TacTip series optic tactile sensor [11] was proposed by the University of Bristol Nathan et al. The TacTip sensor mimics the human fingertip touch-body receptor structure by embedding an array-distributed pin in the colloidal layer, thereby conducting the deformation information on the sensor surface using the camera system to observe the movement of the pin array. Meta's Digit sensor, the [12], optimizes the structure of the sensor to integrate it into the fingertips for robotic operations. In addition, Sui et al. of Tsinghua University have developed the Tac3D tactile sensor [13], which contains an optical path system refracted by four light mirrors and can achieve a virtual binocular imaging effect with a monocular camera. Cui et al. of the Institute of Automation, Chinese Academy of Sciences, have proposed the GelStereo visual and tactile sensing series [14] based on binocular vision, which can obtain binocular tactile images simultaneously and then recover the contact depth information through the stereo matching algorithm.

A soft 3 D force sensor is presented in this paper that can accurately decouple the 3 D force. It is achieved by soft silicone, camera, light source, etc., as shown in Fig.1 (a). The 3 D force information was converted into the image information of the silicon surface, as shown in Fig.1 (c), and a deep learning method was used to decouple the 3 D forces. The proposed force sensor has a small shape, high decoupling accuracy and high flexibility, which is suitable for various operations of robot fingertips.

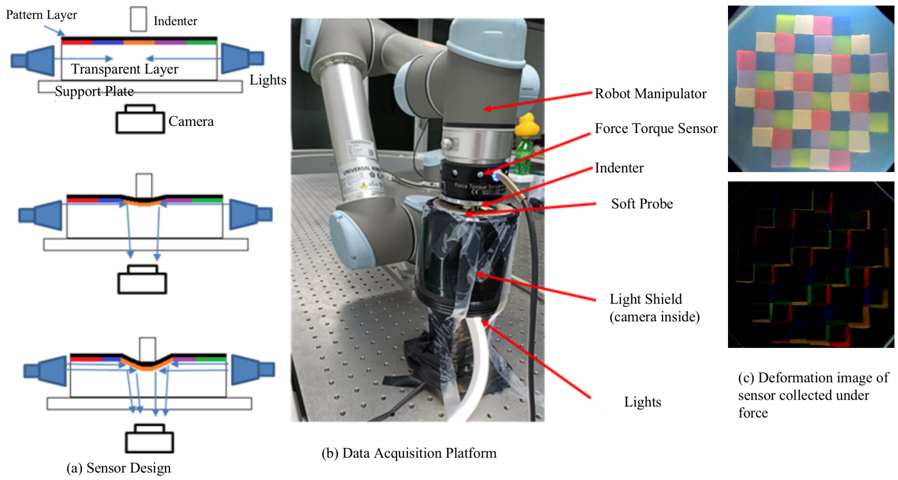


Fig. 1. The principle design of 3d force sensor, data acquisition platform, and the image data collected.

2 Sensing Principle and Sensor Algorithm

2.1 Deformation Mode of the Soft Probe

The main idea of decoupling the 3D force is to record the deformation of the sensor through the camera and calculate the 3D force applied to the sensor through the deformation image taken. As shown in Fig.1(a), place the camera at the bottom of the sensor to capture the silicone deformation. Sorta-clear^{TM}12 silicone gel was used to prepare the sensor. As shown in Fig.2, to obtain quantifiable features, the top of the transparent silicone is covered with a pattern layer made of the arrangement and combination of a plurality of small colored silicone squares of the same softness. The top of the pattern layer is covered with a black silicone layer called the bottom layer. The soft probe consists of a transparent layer, a pattern layer, and a base layer. A transparent bottom plate is placed at the bottom of the soft probe, serving as a support plate for the soft probe so that the soft probe can move relative to the bottom. Light from the LED light source is reflected into the camera through the soft probe. When the soft probe is stationary, i. e., when no force is applied, the light captured by the camera comes from the pattern layer of the soft probe. The following is the analysis and quantification of mechanical deformation and resulting pattern changes in the presence of shear and normal forces. Suppose the silicone is a cuboid with a height of H and a bottom length of L.

Shear Deformation When the upper surface of the soft probe moves in parallel relative to the bottom, the resulting angular shape variable is proportional to the shear force applied to the surface, $F = G\theta$, where G stands for shear coefficient,

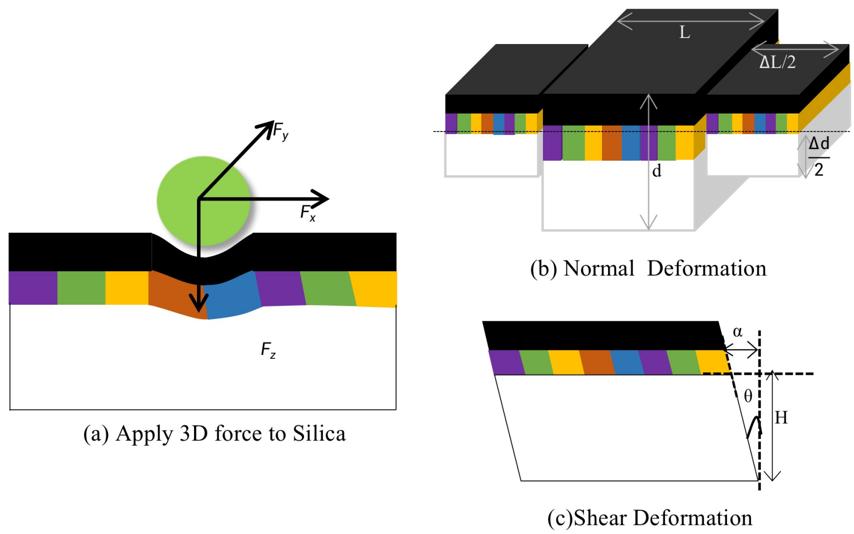


Fig. 2. 3D Force Applied to the Soft Probe Cause the Normal Deformation and Shear Deformation of the Surface

and angular variable θ can be calculated by measuring shear deformation α:

$$\theta = tan^{-1}\alpha/H. \tag{1}$$

Small color squares in the pattern layer will move to different degrees according to the direction and size of the shear force.

Normal Deformation When the cylindrical soft probe stretches along its horizontal axis, according to the poisson effect, the thickness change of the cross-section Δd is :

$$\Delta d = dv\Delta L/L, \tag{2}$$

where d is the original thickness, v is the poisson ratio, L is the length before stretching, and ΔL is the change of length. As a result, the periphery of the pattern layer extends outward.

2.2 Deep Learning Model Adopted to Decouple the 3D Forces

The pixel values of the corresponding image taken by the camera will also change due to the deformation of the color image layer. It is not easy to map the force deformation to the inductive surface. Encouraged by the success of deep learning in tactile perception, this paper presents a convolutional neural network model. Specifically, a multi-output CNN model is used to extract features of high-resolution deformation images and, eventually, get three-dimensional forces. The accuracy of the prediction depends on the sensor material and preparation.

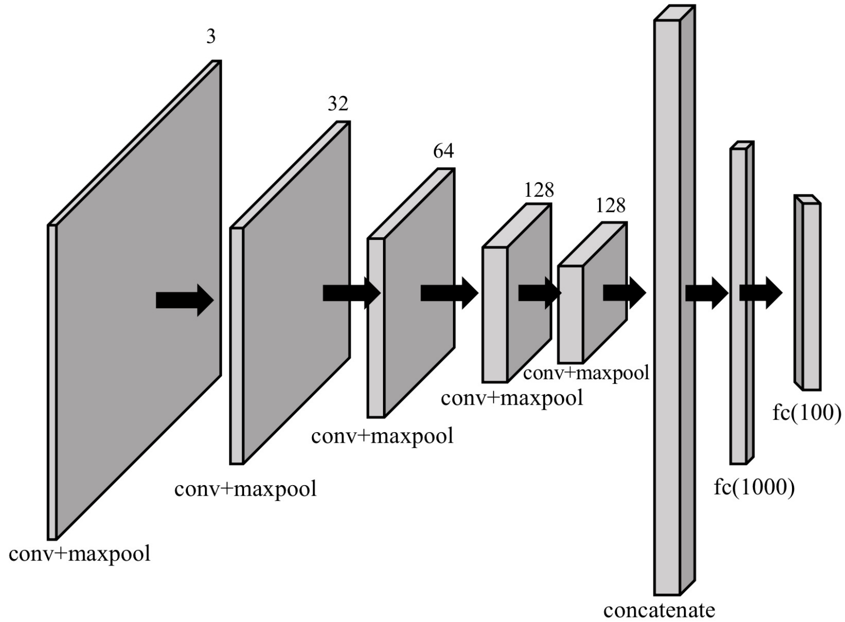


Fig. 3. The Decoupling 3D Force Network Structure

The decoupling 3D force network structure is shown in Fig. 3, divided into feature extraction and regression. The feature extraction block is composed of 4 convolutional layers and pooling layers. The convolution kernel size is 5×5 for the first and second layers and 3×3 for the last two layers, the number of channels is 32,64,128,128, respectively, and the step size is 2. Max pooling size is 2×2, and the step size is 2. Finally, the features obtained by the feature extraction are connected and passed to the regression layer. The regression layer consists of two fully connected layers, and the number of channels is 1000,100. The final output is a three-dimensional force. The means square error (MSE) was used as a loss function to carry out backpropagation during training. The neural network was optimized using a stochastic gradient descent optimizer(SGD), with a batch size of 64 and a learning rate of 10^{-5}. The GPU server Tesla p40 was trained for 120,000 iterations.

3 Experiment and Results

3.1 Automatic Data Acquisition Platform

As shown in Fig.1(b), the main body of the collection platform uses an industrial robot(UNIVERSAL ROBOTS, UR5e Robot), which is used as a force application device and is equipped with a force/torque sensor(ROBOTIC, FT 300-S

Force Torque Sensor) to record force data in real-time. A 20mm diameter indenter is mounted at the end of the force/torque sensor used to act on the surface of the soft probe. Communication with the mechanical arm uses the TCP/IP protocol. A position servo of 125hz was used to control the arm-end-indenter applied to the soft probe at the same speed.

The fabricated sensor is fixed to the optical platform. Before each experiment, the robotic arm's end was moved to the top of the sensor, serving as the start point. The data acquisition process is to reach a given eight depths at a speed of 2mm/s, form different normal forces, under each depth to 1000 different positions, forming a different shear force, back to the starting point after each shear force is applied. Finally, 24000 (1000 $\times$ 8 $\times$3) group sampled data was obtained.

The data acquisition program was written in Labview, which was realized to control the robot manipulator to move to the specified position, automatically obtain the camera image, and synchronously record the 3-dimensional force information. Soft probes vary over time, bringing subtle differences to the image. In order to eliminate the bias, after applying shear force, the robot manipulator will return to the start point to collect the no-force data, each experiment of the normal force (shear force) image minus the original image (no force) to obtain the difference map. The differential-treated dataset is divided into the train set (70%) and the test set (30%) for the deep learning model.

Table 1. Sensor Performance

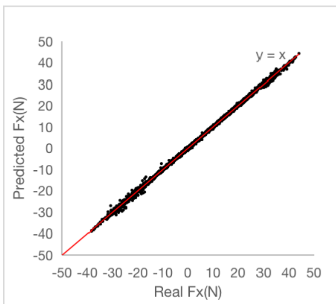
Size		22mm$\times$22mm $\times$22mm
Shore Hardness		12A(soft)
Measuring Range	F_x	$\pm 40N$
	F_y	$\pm 40N$
	F_z	$0-70N$
3D Force Measurement Error(RMSE)	F_x	0.34N
	F_y	0.43N
	F_z	0.68N
Bandwidth		around 30Hz

3.2 Sensor Performance

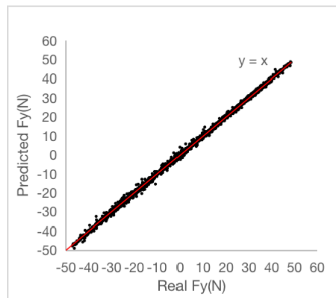
The final response of the manufactured sensor is obtained from the color image, which depends on multiple factors. The size of the sensor depends mainly on the camera, and using a more miniature camera will reduce the size of the sensor. Collect the data into a deep learning model for training and got the root-mean-square error (RMSE) of the test set for F_x, F_y and F_z were 0.34N, 0.43N, and 0.68N. Running under a computer with a graphics processing unit (NVIDIA GeForce GTX 3080 Ti). the sensor bandwidth is around 30hz. The measuring

Table 2. Comparison of state-of-the-art three-dimensional force sensor and force decoupling methods.

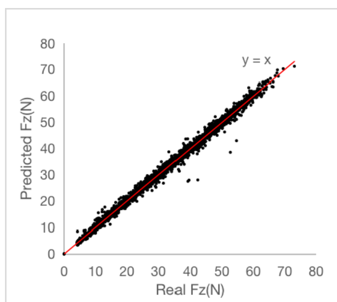
	Gelsight[10]	Digit[12]	Kakani V[18]	Tac3D[13]	GelStereo[14]	Ours
Decoupling force method	Array marker points, finite element modeling	Not reported	Binocular vision, deep learning (vgg-16)	Finite element modeling	Finite element analysis	Deep learning
Normal force (shear force) measurement	Yes	Not reported	Yes	Yes	Yes	Yes
Size	Bulky	20mm*27mm*18mm	Bulky	Bulky	Bulky	22mm*22mm*22mm
Sensor Construction/Features	Bulky, poor model adaptability	Compact, cheap, undeveloped force measurement function	Bulky	Bulky, poor model adaptability	Poor model adaptability	Soft, Strong, Compact,minimum size



(a) F_x result



(b) F_y result



(c) F_z result

Fig. 4. The comparison of the force measured by the designed sensor and the ground truth in x, y and z direction. The red lines represent the ideal result, and the black dots represent measured result.

range of the sensor is shown in Table. 1. Fig. 4 shows that the force measured by the designed sensor is close to the ground truth after the calibration.

Conventional capacitive [5,6] and resistive [7,8] tactile sensors can achieve one-dimensional force (pull force or pressure) measurement, but this method is challenging to achieve in three-dimensional force detection. Because in the detection process, the plane direction of the shear force (Fx, Fy) and the vertical direction of the normal force (Fz) will cause the deformation of the sensor simultaneously, making the generated signals interfere [15]. Through the method of

(a) The Sensors are Fixed on the Gripper at the End of the Manipulator

(b)The Robot Arm Wears Sensors to Grab Fragile Objects

Fig. 5. Color Image under Normal Signal Direction Shear Force

structural innovation [16,17], there are still the problems of complex decoupling process, easy interference and low decoupling accuracy.

Visual-tactile sensors such as gelsight [10]. They introduced the marker point on the reflective film inside the soft elastomer to capture the marker point displacement under the 3 D force. They established the mapping relationship between the marker point displacement and the 3 D force through the finite element analysis to realize the 3 D force detection in the soft environment. Also, using finite element modeling are the Tac3D [13] and GelStereo [14]. However, the established three-dimensional force model is relatively small due to the need to set more preconditions and simplify the problem in finite element modelling. Meta's Digit sensor [12] optimizes the structure of the sensor to integrate it into the fingertips for robotic operations, but force measurements are not reported. Kakani et al. [18] improved the VGG-16 deep neural network to measure the contact position, the contact area, and the contact force distribution of the binocular tactile images. Still, the sensor structure is bulky and difficult to use. As shown in Table. 2, the designed sensors are based on optical principles, which not only can accurately measure the 3 D force compared to the existing optical tactile sensors but also are the smallest size of the current optical tactile sensors and are very soft.

Using the sensors studied in this paper, the grasping of fragile objects can be achieved. As shown in the Fig.5, attaching the sensor to the clip claw at the end of the robotic arm can receive and control the magnitude of the force while grasping the fragile object so that the fragile object will neither fall nor be crushed. Thus, the force control problem in the process of grasping the fragile object is solved.

4 Conclusion

To detect 3 D forces under soft conditions, this paper designs a structurally innovative sensor, ranging from data acquisition to data analysis and processing to hardware implementation. This study can be used for force control in robot compliant control, which is expected to solve the problems in the robot field and promote the intellectual development of robots. In the future, it is hoped to realize the update and iterative development of soft 3D force sensors and hope to realize mechanical arm force control equipment to solve different mechanical arm control problems.

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