A Thin Format Vision-Based Tactile Sensor With a Microlens Array (MLA)

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Abstract—Vision-based tactile sensors have been widely studied in the robotics field for high spatial resolution and compatibility with machine learning algorithms. However, the currently employed sensor’s imaging system is bulky, limiting its further application. Here, we present a microlens array (MLA)-based vision system to achieve a low thickness format of the sensor package with high tactile sensing performance. Multiple micromachined microlens units cover the whole elastic touching layer and provide a stitched clear tactile image, enabling high spatial resolution with a thin thickness of 5 mm. The thermal reflow and the soft lithography method ensure the uniform spherical profile and smooth surface of microlenses. Both optical and mechanical characterizations demonstrated the sensor’s stable imaging and excellent tactile sensing, enabling precise 3-D tactile information, such as displacement mapping and force distribution with an ultracompact thin structure.

Index Terms— Microlens array (MLA), miniaturized tactile sensor, optical tactile sensor, vision-based tactile sensor.

I. INTRODUCTION

Vision-based tactile sensors have emerged as a new type of a tactile sensing method to provide abundant contact information [1], [2], [3], such as surface texture [1], depth [2], force distribution [3], contact geometry [4], and slip [5]. High spatial resolution and compatibility with sophisticated image-based machine learning are two significant advantages of vision-based sensors compared with conventional tactile sensors that depend on other transduction principles, such as piezoresistive and capacitive mechanisms. Conventionally, the vision-based tactile sensors capture the image using one monocular camera module [1], [2], [3]. However, the traditional monocular lens system lacks the miniaturized size and large field of view (FOV). Meanwhile, in some other optics applications, prototypes with multiple vision units have been developed, such as TOMBO [6], APCO [7], and Cley [8], with compact structures and wide FOVs. These prototypes obtain multiple images by separating one image sensor to multiple sections. Therefore, in this article, the microfabricated multiple vision units are adopted as the imaging system for vision-based tactile sensors, and the microlens array (MLA) is utilized in the device for enhancing image quality. Simultaneously, the comparison between pinhole and MLA based on the vision-based tactile sensors is reported.

As the imaging system’s key component, the MLAs have been widely applied in optoelectronic systems [9], [10], micro-electromechanical systems (MEMSs) [11], [12], and bionic devices [13], [14], [15], [16], [17], [18]. The lens array’s refractive index, dimensions, and uniformity are representative factors for MLAs’ characterizations. Compared with micro-pinhole arrays, higher resolution and less light intensity requirement are two advantages of MLAs. However, the utilization of MLAs also brings the challenge of optimizing optical distance for both image plane and object plane. Besides, the difficulties in controlling lenses’ profiles still exist for the applications requiring a submillimeter MLA. In addition, the crosstalk between vision units affects the
imaging quality of multivision systems as presented in the previous artificial compound eye systems [13], [15], [18]. In our work, the imaging quality between two adjacent vision units is guaranteed using the proposed walls to isolate the individual lens of MLAs.

Fabricating MLAs is another challenge, since low processing cost, fine control of lens parameters, and smooth surface need to be achieved simultaneously. Among various techniques to develop MLAs, the thermal reflow method [19], [20], [21] using lithography can provide a better controllable profile than inkjet printing [22], [23] and hot embossing [24]. Meanwhile, for the lens replication, soft lithography technology is one of the most effective techniques [25]. Among different materials, which can be used in the soft lithography technique, polydimethylsiloxane (PDMS) is regarded excellent for its high transmittance [26] and smooth surface [27]. Furthermore, the lens using PDMS can be applied to tunable imaging [18], [28], [29], [30] and vari-focus imaging fields [31], [32].

In this study, an MLA-enhanced vision-based tactile sensor is developed. Scaled MLAs are designed, fabricated, and assembled in the tactile sensor to satisfy application requirements. The optical properties, such as the focal length and imaging resolution, are quantitatively evaluated. The spatial resolution of MLAs is tested compared with the results using pinhole arrays, where the spatial resolution is improved using MLAs with magnified images. After assembling the imaging components into the tactile sensor, normal and tangential force calibration with a commercial force sensor and several objects’ contact experiments are executed and evaluated. The sensor’s stable image output and response to the contact force (normal and tangential force) verify the excellent sensing abilities of the tactile sensor with MLAs.

II. RESULTS AND DISCUSSION

A. Schematic of the Sensor Using MLA

The schematic of the vision-based tactile sensor using an MLA is shown in Fig. 1(a). The tactile sensor comprises three main subsystems: touching, imaging, and supporting subsystems. The touching subsystem includes an elastomer layer, a pattern layer (where markers are embedded), a reflective layer, and a protection layer. Below the touching subsystem, the imaging subsystem consists of the isolated square chamber structure, an MLA, and a complementary metal–oxide–semiconductor (CMOS) image sensor (CIS). The square chamber structure is double-side etched from the monocrystalline silicon. Here, the CIS (OV 2710, OmniVision) is utilized. The supporting subsystem contains the supporting frame and illumination source. The tactile sensor using the pinhole imaging method is shown in Fig. 1(b). Compared with the pinhole method, an MLA is placed onto the pinhole structure where the pinhole is used to define the aperture. The combination of MLA and the aperture of pinhole structure can have a more extended depth of field, which benefits the touching subsystem when the elastomer layer is deformed due to external contact. The MLA has a convex shape and faces the touching layer rather than facing the CIS to amplify the imaging details.

The fabricated lenses have excellent smoothness and near-ideal shape in Fig. 1(c). The roughness is illustrated by the mean value $R_a$ of 0.024 $\mu m$ in $1\times 1 - \mu m$ area (Fig. S1, Supplementary Material), which is comparable to previous work [33]. The MLA profile and parameters are shown in Fig. 1(d). Accordingly, the schematic of the optical design with parameters is shown in Fig. 1(e). Using the thermal reflow technique, the spherical lens shape is guaranteed, and the measured profile fits well with the theoretical spherical one [see Fig. 1(f)]. The Pearson correlation coefficient between these two curves is 0.99994, verifying the strong fitness of the experimental and theoretical results. The spherical curve equation is listed as follows:

$$R = \frac{h}{2} + \frac{D^2}{8h}$$

where $R$ is the radius of the spherical shape, $h$ is the sag height, and $D$ is the sag diameter. The fabrication process flow of the MLA is demonstrated in Fig. 1(g). The fabrication detail of MLA is described in the Methods and Materials. It is worth noting that the utilization of the chlorosilane [34] is necessary for peeling off the plano-convex lens from the concave lens mold. At the same time, the pinhole structure and the square isolating chamber structure were formed using double-side etching of a silicon wafer [35]. The multiple vision imaging system using MLA on the square isolating chamber structure was aligned and assembled. The transparency test in Fig. S2, Supplementary Material, shows its high transmittance ability (around 95%) in the visible wavelength area, which is close to a commercialized BK7 glass lens.

B. Optical Properties

Different to other tactile sensors that transduce contact signals to the electrical output, vision-based tactile sensors rely on images to analyze the force stimuli from outside. To quantitatively evaluate the images, the optical properties of MLAs were studied. The MLAs with a sag height from 80 to 140 $\mu m$ and different focal lengths and numerical aperture (shown in Fig. S3, Supporting Information) were also tested. After balancing the radius curvature, the pinhole diaphragm radius, and the working range of the touching layer (details in optical parameters, Supporting Information), the MLA with a 640-$\mu m$ diameter and a 120-$\mu m$ sag height was selected.

With a specific focal length and an image distance, the object distance is determined, and at the same time, the depth of field is determined by both the lens and aperture’s diameter.

The measurement schematic setup is shown in Fig. 2(a). The MLA is placed on the three-axis movement platform. The light is emitted from the lamp and refracted by the mirror. With the collimator lens L1, the light is evenly transmitted to the MLA. In Fig. 2(b), focusing images of 12 vision units are shown by the above experimental setup. The light intensity distribution is shown in Fig. 2(c). It should be noted that all 12 units demonstrate similar light intensity where the variation is no more than 10%. Fig. 2(d) shows the MLA modulation transfer function (MTF) curve using the slanted-edge calculation from spatial frequency response. The ISO12233 testing chart is used as the edge image source. Using the
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Fig. 1. (a) Schematic of the multiple vision units-based tactile sensor with an MLA. (b) Schematic of the multiple vision units-based tactile sensor with pinholes. Here, the multiple vision units are achieved by using the pinhole structure with MLA on one image sensor. (c) Surface morphology of the MLA. The inset image illustrates the zoomed-in profile of the single lens unit. (d) MLA profile and parameters of one plano-convex lens. (e) Schematic of the optical design with parameters. (f) Profile of a single lens unit with a measured and theoretical spherical curve. (g) Process flow of fabricating and assembling the MLA on the pinhole structure.

C. Imaging Test

The imaging test is performed, as shown in Fig. 3(a), using letters U, S, and T (the inset image shows the schematic setup of the imaging tests using letters U, S, and T from mobile phones). To test the spatial resolution used in the tactile sensor, a dot image test was performed using circular dots in Fig. 3(b) and (c). Movie S1, Supplementary Material, clearly shows the movement with these two imaging methods using the same object. Blob detection is used here to capture the area and the central point displacement. With Z-directional moving to the far side, the area of the dot decreases. In Fig. 3(d), the linearity of the MLA result ($R^2 = 0.98$) is better than the pinhole result ($R^2 = 0.88$). It proves that using MLA...
leads to a more precise image while pinhole imaging leads to a blurry image. The gradient of the MLA curve is around 2.7 times of the result of the pinhole, indicating the superior ability in the spatial resolution range with magnified images. The $XY$-directional movement experiments were carried out, as shown in Fig. 3(e), and three heights in the working range were adopted (noted as height $A$, $B$, and $C$, where height $A$ denotes the 4.8-mm distance between the dot and the CIS, height $B$ denotes 4.9 mm, and height $C$ denotes 5 mm). It is worth noting that the gradient of lens curves is higher than the pinhole curves, indicating the higher resolution (around 1.48 times) in the $XY$-movement directions. Besides, the nearer the pattern is, the more displacement should occur with the same step length, which means the gradient of height $A$ should be the highest, and the gradient of height $C$ should be the lowest. The result from the lens agrees well with the above theory, while the pinhole curve result does not fit well. In the results for pinhole curves, the gradient of height $A$ (85.6) is lower than height $B$ (94.7), which means that in the small range, the threshold set in the blob detection cannot detect the difference of the dot’s displacement between these two heights. It indeed indicates the lower spatial resolution in this working range of pinhole compared with the MLA.

### D. Stitched Image and Force Indentation Calibration

The aforementioned imaging subsystem was assembled with the other two subsystems (touching subsystem and supporting subsystem) to form the proposed tactile sensors, as shown in Fig. 4(a). In Fig. 4(b), two types of color patterns [36], [37] with different pattern densities (Target A and Target B) are adopted as objects using MLA and pinhole, separately. It proves that the light intensity required for the MLA imaging is much lower than that with the pinhole imaging system. Besides, using MLA in the prototype, a more detailed and magnified image can be obtained with the below images. The MLA contributes to capturing an image without illumination sources when the same image is too dark to recognize using pinholes. The prototype with LEDs (as illumination source) and without LEDs is demonstrated in Fig. S5, Supplementary Material. In Fig. 4(c) and (d), a spherical object is used to press the touching subsystem, and two images are illustrated for its deformation procedure. The experimental setup is shown in Fig. S6, Supplementary Material. The inset image demonstrates the colorful pattern with a 40× microscope. Movie S2, Supplementary Material, demonstrates the normal and tangential movement after stitching the multiple images.
Here, we adopt two calculated signals [35], area factor (AF) and tangential factor (TF), to calibrate with the reference commercial sensor’s normal force and tangential force. The equations to obtain AF and TF are shown as follows:

\[
AF = \sum_{i=1}^{N_p} \left( \frac{S_i}{S_i^{\text{init}}} - 1 \right) 
\]

\[
TF = \frac{\left| \sum_{i=1}^{w-h} U_i \right|}{w \cdot h} 
\]

where \( N_p \) is the number of patches segmented for area calculation, \( S_i \) and \( S_i^{\text{init}} \) denote the area and area of the first frame of \( i \)th, \( w \) and \( h \) are width and height of optical flow frame patch, and \( U_i \) denotes the optical flow generated from coarsest level with largest patch size to finest level with smallest patch size. The computation of AF and TF considers both the accuracy of depth estimation and the average error due to the accumulated pixel tracking error in optical flow. With the increased number of scatter points in AF calculation, the resulting depth estimation can be smoother and closer to the actual surface. However, the result will be less stable due to the oscillating error in the displacement vector field. The computation speed also drops significantly. Therefore, we finally chose \( 16 \times 13 = 208 \) points to achieve a relatively good calculation quality. For the normal indentation [see Fig. 4(e)], three positions were tested with the spherical object, and the regressed line illustrates the good linearity (\( R^2 = 0.97 \)). For the tangential movement, the depths of 0.1, 0.3, and 0.5 mm were selected. The deformation images are shown in Fig. 4(d).

Fig. 4(f) gives the calibration result from the calculated TF and tangential force from the sensor. It is noticeable that the deeper the indentation, the bigger the tangential force it will cause. The regressed line (\( R^2 = 0.96 \)) also demonstrates the good linearity of the sensor response.

After calibration with the force sensor, several small objects (staple and coin edge) were pressed onto the tactile sensor for demonstration, as shown in Fig. 5(a). By the operations...
Fig. 4. (a) Prototype of the tactile sensor with an MLA. The red inset image shows the MLA on the square isolation chamber structure, and the pinhole structure is put on the CIS. The middle one shows the tactile sensor with MLA embedded. The yellow inset image shows the colorful pattern embedded in the supporting frame. (b) Two types of color patterns are tested as Target A and Target B. The top two images show the denser color pattern (Target A) using MLA and pinhole without an illumination source, respectively. The bottom two images show the sparser color pattern (Target B) using MLA and pinhole with illumination. (c) Left—stitched results of normal directional indentation with a spherical object. The inset image illustrates the random color pattern’s appearance with a 40× microscope. The deformation fields are demonstrated with a small and a large indentation, respectively. (d) Left—stitched results of tangential directional indentation with a spherical object. The deformation fields are illustrated with the tangential movement. (e) Normal indentation experiment is carried out by pressing three positions on the elastomer layer. The normal force is obtained from the commercialized force sensor, while the area factor is calculated from the deformation field. (f) Tangential movement experiment is carried out by moving the object while keeping the indentation depth in three different levels. The tangential force is obtained from the commercialized force sensor, while the tangential factor is calculated from the deformation field.

Fig. 5. (a) Objects’ indentation on the tactile sensor. Left—staple indentation using its corner. The width of the staple is around 0.5 mm. Middle—indentation using two sharp points of the staple. Right—rotational movement using the edge of a coin. The raw images before processing clearly show the indentation procedure with small objects. (b) Deformation field in top view and isometric view of above three type indentations. Three videos show the indentation process and deformation fields (Movie S3–S5). (c) Number “1” profile pressing by around 100 µm from stage 2 to stage 3. (d) Depth images of numbers “0,” “1,” and “2,” which are obtained from the deformation filed images by interpolation. The deformation field, depth image, and size of number “4” are listed at the bottom.
of image stitching and surface deformation tracking [35], the deformation fields are obtained in the top view as well as the isometric view in Fig. 5(b). The deformation fields produced by several objects illustrate the sensor’s ability to perceive objects of submillimeter size. Furthermore, Fig. 5(c) illustrates by several objects illustrate the sensor’s ability to perceive deformation fields are obtained in the top view as well as the image stitching and surface deformation tracking [35], the comparison of our sensor and other different requirements of the MLA’s profile, the photoresist was fabricated, characterized, and tested. The thermal reflow was fabricated, characterized, and tested. The thermal reflow process was utilized for the developing stage. After developing, the photoresist was then placed in an oven at 120 °C over 12 h. Then, PDMS (Sylgard 184 Silicone, Dow) was mixed with a 10:1 ratio of bising material and curing agent. After degassing, the mixture was spin-coated on the silicon wafer. The concave PDMS MLA mold was obtained after 4-h baking in an 80 °C oven. Trichloro (1H,1H,2H,2H-perfluorooctyl) silane (Sigma, Aldrich) was used to treat the surface of the concave MLA mold. The second PDMS (mixing ratio of 5:1) molding was then processed. The plano-convex multiple lens array was finally formed by pouring, curing, and peeling off PDMS from the transferring mold.

### B. Morphology Characterization

The morphology images were captured by the scanning electron microscope (Model JSM-6490, JEOL). The lens’ height and diameter were measured by the profile (P-10, KLA-Tencor).

### C. Optical Property Characterization

The transmittance of the PDMS was measured by the UV/VIS spectrophotometer (Lambda 20, Perkin Elmer). The LED ring shape lighting source (MIC-199, POMEAS) was calibrated by the lens (GCO-2410, Daheng Optics). The focusing and letter image tests were obtained by a camera (DFK 33UP5000, Imagingsource) with 1-in ON CIS with 4.8-μm pixel size. The MTF curve was carried out with the help of open-source ImageJ [38]. The simulation result of the MTF curve was obtained using Zemax. The image sensor (OV 2710, OmniVision) was utilized for the tactile sensor device.

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