Visuotactile Sensors with Emphasis on GelSight Sensor: A Review

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***Abstract*—This review paper focuses on vision and touch-based sensors known as visuotactile. The study of visuotactile sensation and perception became a multidisciplinary field of study by philosophers, psychologists, biologists, engineers, technologists, and roboticists in the fields of haptics, machine vision, and artificial intelligence and it dates back centuries. To the best of our knowledge, the earliest records of visuotactile sensor was not applied to robotics and was not even for hand or finger imprint analysis yet for recording the foot pressure distribution of a walking or standing human known as pedobarograph. Our review paper presents the different literature related to visuotactile sensors that lead to a high-resolution miniature pedobarograph-like sensor known as the GelSight sensor. Moreover, this review paper focuses on architecture, different techniques, hardware, and software development of GelSight sensor since 2009 with its applications in haptics, robotics, and computer vision.**

***Index Terms*—GelSight sensor, haptics, visuotactile**

I. INTRODUCTION

HUMANS can construct representations of the world by detecting different stimuli from their environment through their sensory receptors and convert them into neural signals [1], [2]. Transduction is the conversion of one form of energy to neural impulses while sensation is how our nervous system receives and represents the stimuli from our senses. Moreover, humans can organize and interpret different sensory information to recognize meaningful patterns and events in a process known as perception. According to Myers [1], sensation and perception work together in one continuous process to help humans navigate, understand, and adapt to the complexities of the world.

Aside from sensation and perception, humans can learn from experiences and have the capacity to store learned experiences in the form of memory which can be retrieved at a later time. Humans remember information not only from external sources (obtained through the perceptual process) but also from reasoning, thought, and imagination. The process by which human attributes a memory to an external or an internal source is called reality monitoring [3]. Human sensation, perception, learning, memory, and reality monitoring have analogies in the field of robotics. Sensors, also known as transducers, are hardware devices that gather or measure different forms of energy from the environment and convert them to another form of energy such as electric or light (analogous to human sensing). Computer software can process, organize, classify, and interpret the information from the sensors (analogous to human perception) through artificial intelligence algorithm that learns (analogous to human learning) from data-sets (analogous to memory).

Among the basic human senses of sight, hearing, touch, smell, taste, kinesthetic, and vestibular [1], this review paper focuses on sight and touch which will be termed as visuotactile for the rest of the paper. Psychologists estimate that 80% of information humans obtain from the environment is through visual pattern [4]. Moreover, haptic perception is the natural recourse when visual perception is impaired [5]. Curiosity on visuotactile sensation and perception dates back to the 18th century [6] inspired by the famous Molyneux's question stated briefly as to whether a person born blind might immediately identify a cube and a sphere previously familiar to him only by touch if he was made to see [7]. Molyneux's question is related to visuotactile sensation and perception which was initially treated as a problem of philosophy as discussed by Morgan [6], but later on it was tackled by psychologists under the field of developmental psychology studying visuotactile perception and coordination that dates back in the 1970's as reported by Zhang [8]. The study of visuotactile perception became a multidisciplinary field of study not only by philosophers and psychologists, but also by engineers, technologists, and roboticists in the fields of haptics, tactile robotics, machine vision, and artificial intelligence [1]–[10].

This paper reviews the different literature related to visuotactile sensors with emphasis on GelSight sensor [11]. The visuotactile sensor converts physical contact into an image. The physical contact modulates the visible light within the sensor to produce a tactile image. The visuotactile image

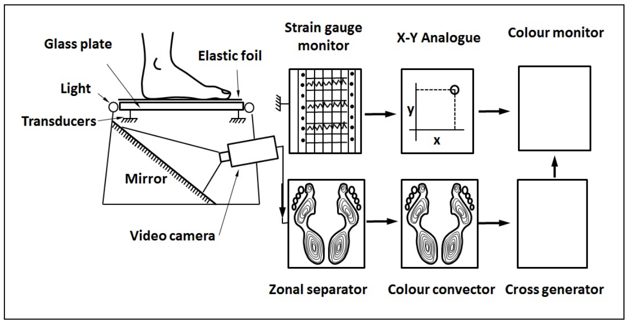

Fig. 1: Optical pedobarograph setup as presented in [14].

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can be analyzed in real-time using a computer or it can be recorded and stored for future processing and analysis. It can be a tactile image that contains tactile markers or optical flow vector arrows, but can also be a retrographic image [11] that can be used for metrology, 3D image reconstruction, and object recognition or classification. In our opinion, an ideal visuotactile sensor is like a flexible mirror with the resolution of the human eye and the sensitivity of human skin as stated by the great philosopher in his “Diderot’s Letter on the Blind” [6].

II. VISUOTACTILE SENSORS

To the best of our knowledge, pedobarograph can measure and record pressure distribution under the feet, which is the earliest known visuotactile like the sensor developed by Chodera in 1950’s to 1960’s [12], [13]. The optical pedobarograph in Fig. 1 [14] has a fine surface made of elastic foil or plastic foam put on top of a transparent plate on which a human can stand or walk on. Light from the side of the transparent plate is diffused by Total Internal Reflection (TIR). A foot pressure distribution pattern is generated as the foot presses the elastic foil. An isobaric map can be formed and each zone can be represented by a different color. The pattern that can be observed or recorded is a picture of light intensity reflected through the plate [14], [15].

Design and development of miniature pedobarograph-like visuotactile sensors that can be fitted on a robotic arm started during the 1960’s at the MIT lab as reported in [16]. One of which is the 1963 visuotactile sensor developed by Kappl that used a photoelastic material (polyurethane rubber) as a pattern generator similar to a polariscope as shown in Fig. 2a. The polyurethane is more or less transparent and does not normally affect light passing through it. The photoelastic material has a reflecting paint on one side and a polaroid sheet on the other side with plexiglass backing. When strained, this device polarizes light passing through it and produces a phase shift proportional to the strain. Three years after Kappl’s visuotactile design, Strickler and Sheridan [16] introduced a visuotactile sensing system for a remote manipulator and the design schematic is shown in Fig. 2b. They investigated various methods of producing high contrast optical stress patterns with the use of fiber optics and television system. The visuotactile sensing system for a remote manipulator with a fixed pattern whose reflection is viewed in a flexible mirror is shown in Fig. 2c.

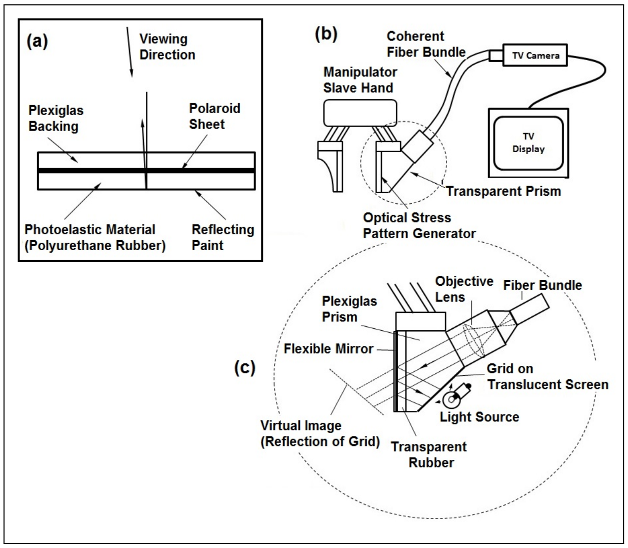

Fig. 2: (a) The visuotactile transducer was developed by Kappl in 1963 [16], (b) the schematic of visuotactile sensing system for remote manipulator, and (c) the visuotactile sensor design with a reflected grid pattern [16].

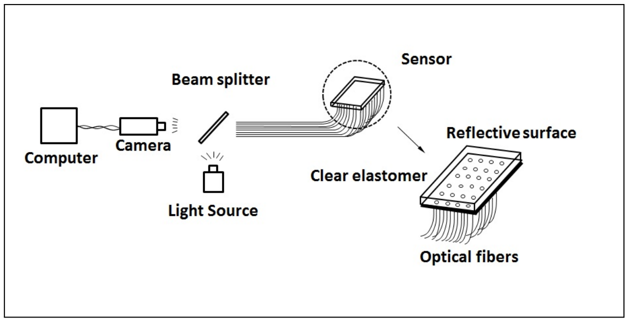

Fig. 3: High resolution optical touch sensor setup (1984) reported in [17].

In 1984, Schneiter and Sheridan from MIT [17] reported that they designed, built, and demonstrated an optical touch sensor for robots. The set-up diagram is shown in Fig. 3. It has a flexible material with reflective coating and uses optical fiber technology. According to [17], the device is not affected by electromagnetic noise. The pattern generated is analyzed by a computer using image processing algorithm that detects slip and orientation changes by calculating the centroid and moments of inertia of the thresholded difference picture. Discrete Mohr’s circle analysis is performed to determine the principal axes of the image. This optical touch sensor design achieved high spatial resolution of 2100 sensitive points per square inch.

In the same year, Tanie et al. from Japan [18] reported that they developed a small high-resolution pedobarograph-like tactile sensor using the pressure-optical conversion technique. The sensor system consists of a transparent acrylic plate

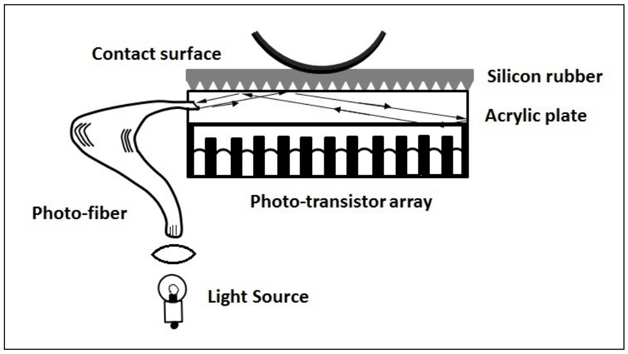

Fig. 4: General lay-out of high resolution planar optical touch sensor (1984) reported in [18].

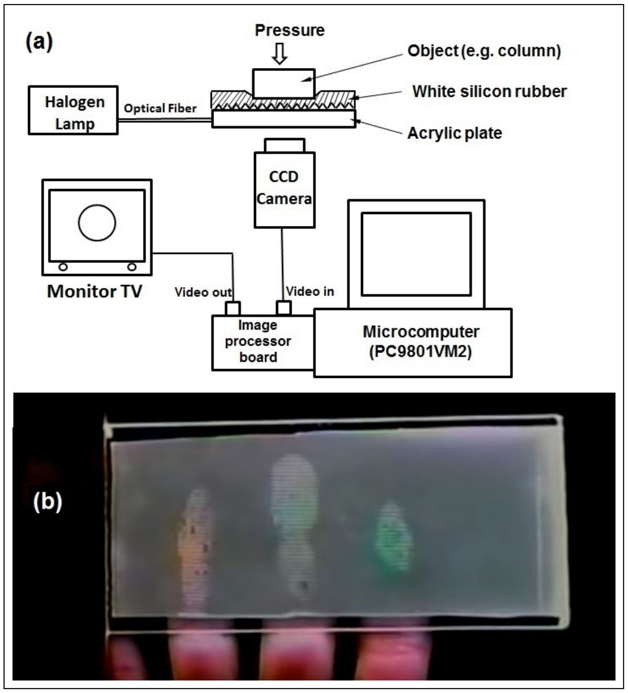

Fig. 5: (a) The setup of flat-plate visuotactile sensor with a CCD camera (1988) reported in [19], and (b) a camera view of the flat-plate visuotactile sensor (1988) taken as a snapshot from the video presented in [20].

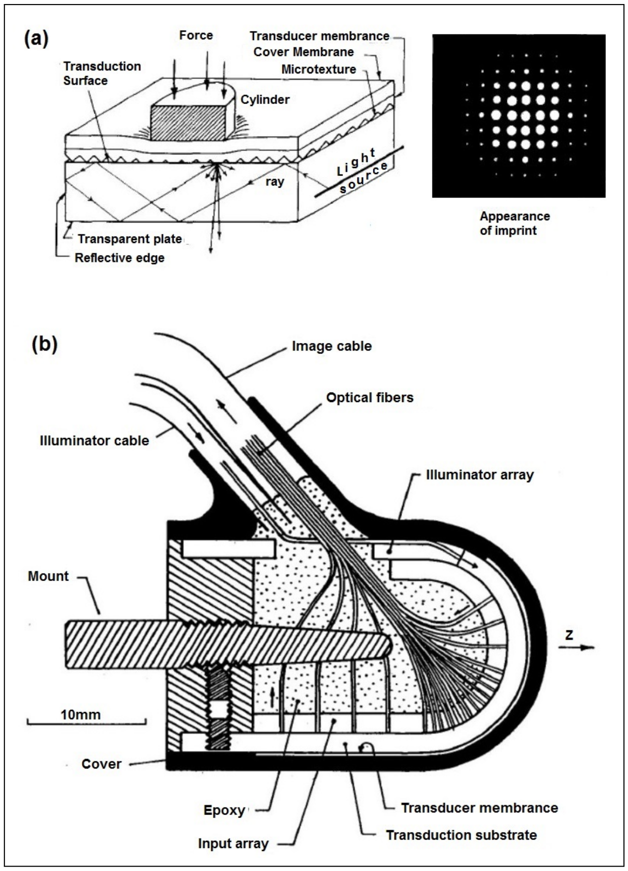

Fig. 6: Begej's experimental setup as reported in [21]: (a) The planar sensor components for sensing force or pressure distribution by TIR, and (b) cross-section of the fingertip-shaped sensor.

(56mm x 117mm), an elastic sheet, a light-guide made of plastic fibers and a 32xl6 phototransistor array as shown in Fig. 4. In this sensor, light-guided via a light-guide was incident upon one end of the plate. The light conducts in the plate by TIR if no pressure is applied on the elastic sheet. Pressure applied onto the sheet causes optically active contact between the sheet and the plate whereby the TIR conditions are changed and the light illuminates the sheet.

Tanie et al. [18] planar optical touch sensor resolution was greatly improved with the use of Charged Coupled Device (CCD) camera as reported in [19]. This planar high-resolution visuotactile sensor can be used to capture the precise profile of a 3D object using a CCD camera. The sensor setup and the flat-plate visuotactile sensor are shown in Fig. 5a and Fig. 5b respectively.

Another CCD camera-related visuotactile sensor was reported in 1988 by Begej [21]. Begej's design focused not only on planar but also on finger-shaped visuotactile sensors for robots as shown in Fig. 6a and Fig. 6b respectively. This visuotactile sensor operates on TIR to produce a gray-scale image of the contacted object's normal forces. Begej's planar visuotactile sensor has a 32x32 sensor array for parallel-jaw gripper. CCD camera and fiber optics technology have been used in a microprocessor-based image analysis system. It contains 256 sensing points dispersed in a dual-density pattern with a tactile fovea near the tip with a size of 13x13mm having 169 taxels.

During the 1990's, Maekawa et al. developed three versions of a finger-shaped visuotactile sensor using an optical waveguide [22]. It is like the flat-plate visuotactile sensor in [18] formed into a hemispherical shape. The test setup of finger-shaped visuotactile sensor is shown in Fig. 7(a) and the three versions of sensors are shown in Fig. 7(b), (c), and (d) respectively. The first prototype developed in 1990 has a diameter of 54mm [23], the miniaturized version developed in 1991 has a diameter of 32mm [24], and the fingertip-sized version developed in 1992 has a diameter of 20mm [25].

In the mid-1990's, Ohka et al. developed a three-axis visuotactile sensor [26], [27] as shown in Fig. 8. This visuotactile sensor uses different kinds of feeler arrays to detect 3-axis force components. It was found that for an extremely soft object trapped in the array of column feelers, three-axis force cannot be detected by the column and cone feelers as shown in Fig. 8b. Moreover, it was reported in [27] that the sensor consumes considerable calculation time acquiring such tactile information as material, texture, shape, and slippage. Therefore, the 3-axis visuotactile sensor was modified to address the above issue by introducing a flat sheet of rubber on top of an acrylic plate with pyramidal projections as shown in Fig. 8c. The rubber sheet has square concave portions (soft rubber) and convex portions (hard rubber). A 2x2 array of pyramidal projections is aligned to each concave or convex portion. The 3D force applied can be inferred from the contact areas of the projections [27].

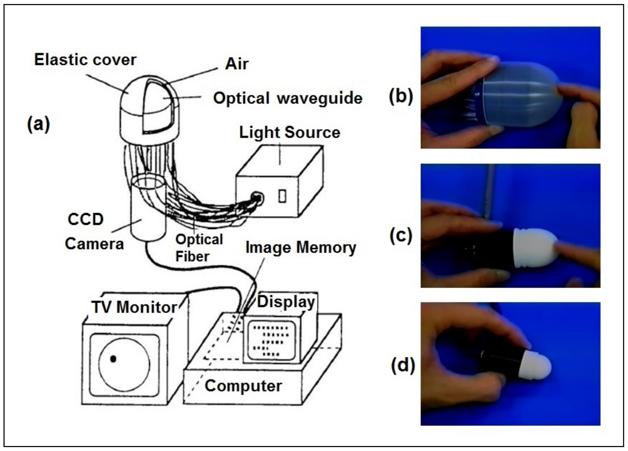

Fig. 7: The finger-shaped visuotactile sensor experimental setup [22]: (a) CCD camera based finger-shaped visuotactile sensor with an elastic cover converts pressure to an image through TIR like the flat-plate visuotactile sensor, (b) the first prototype developed in 1990 has a diameter of 54mm [23], (c) the miniaturized version developed in 1991 has a diameter of 32mm [24], and (d) the fingertip-sized version developed in 1992 has a diameter of 20mm [25]. Pictures are snapshots taken from [20].

In the year 2000, a human-fingertip-like visuotactile sensor with deformable membrane and skin markers has been developed in Harvard Robotics Lab [28]. It has a metal housing that holds the camera, transparent window, and a roughly elliptical latex membrane filled with transparent gel that acts as the sensing area. The inner surface of the membrane has grid dots drawn at specific locations. A metal fingernail supports the membrane. The visuotactile fingertip sensor with schematic as shown in Fig. 9 has dimensions of 6.2cm in length and a base diameter of 2cm.

From the visuotactile sensors discussed so far, none of them modified the internal structure of the flexible membrane. All modifications and improvements are on the external structure by adding reflective skin in the forms of foil [12]–[15], paint [16], markers [16], [28], and the flexible mirror [16]. External feelers were also added to the flexible material to make it capable to measure three-axis forces [26], [27].

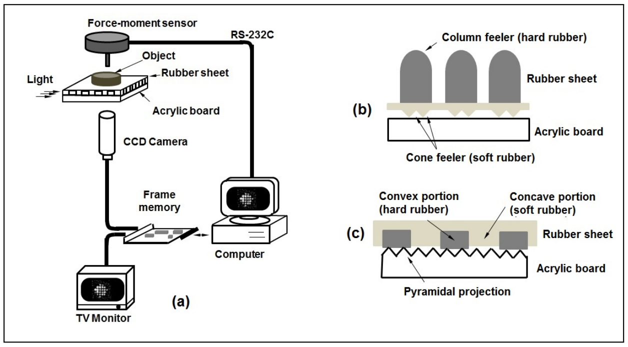

Fig. 8: (a) Experimental setup for 3-axis visuotactile sensor presented in [27]. Two versions of 3-axis sensors presented in [27]: (b) the sensor with a column and cone feelers and (c) the sensor with a plane sheet of rubber on top of an acrylic plate with an array of pyramidal projections.

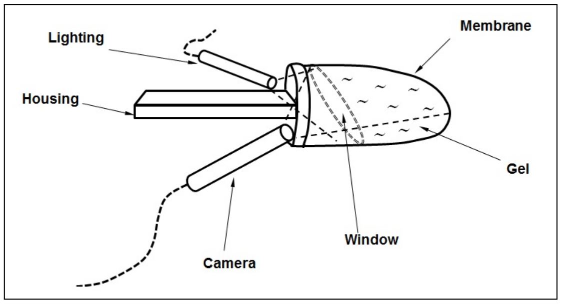

Fig. 9: Human-fingertip-like visuotactile sensor with deformable membrane and skin markers (2000) reported in [28].

In 2001, a new form of visuotactile sensor from Tachi Lab, Japan was designed and introduced. This visuotactile sensor can measure a 3D vector distribution [29]. The experimental setup of this visuotactile sensor is shown in Fig. 10. The internal structure of the flexible material has been modified by adding blue and red beads inside the flexible material. This 2001 visuotactile sensor has been named as the GelForce in 2004 [30]. An in-depth discussion and evaluation of the GelForce sensor were published by Kamiyama et al. in 2004 [31]. From the bulk device of 2001, the GelForce sensor was miniaturized by Sato et al. in 2008 in the form of a finger-shaped GelForce [32], [33] as shown in Fig. 11a. Moreover, Sato et al. improved the finger-shaped GelForce in 2011 by adding it with a thermo-sensitive paint layer in its elastic sheet to sense temperature mimicking a human finger [34]. The cross-section of this finger-shaped GelForce with temperature sensing ability is shown in Fig. 11b.

Aside from the GelForce sensor, there are other visuotactile sensors that modified the internal structure of the flexible material by embedding markers. In 2019, Sferrazza et al. [35] developed a visuotactile device that has fluorescent green spherical markers randomly embedded in the flexible material as shown in Fig. 12a. Like in the case of the GelForce sensor, force and pressure applied to the sensor are inferred from the movements of these fluorescent green markers which are tracked by computer vision algorithm. Moreover, Lin and Wiertlewski [36] developed a visuotactile device in 2019 with embedded dye markers in the flexible material. Instead of spherical makers, semi-transparent two color dye markers arrange in two layer arrays that overlap as shown in Fig. 12b. The shear and normal deformation can be inferred via subtractive color mixing when the markers show blends of colors depending on the displacement at the surface.

In 2008, the same year when finger-shaped GelForce was introduced, a new biologically inspired visuotactile sensor with artificial papillae was developed in Bristol Lab, in the UK [37]. It is like a synthesis of the previously discussed finger-shaped hemispherical dome visuotactile sensors of the 1990's [22]–[25] combined with column feelers reported in [26], but has a skin cover which eliminates the issue of small objects being trapped in the array of column feelers reported in [27].

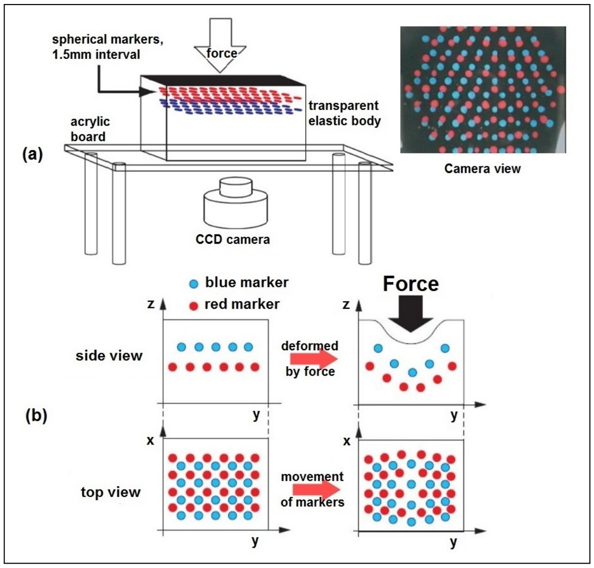

Fig. 10: The GelForce sensor: (a) Experimental setup, and (b) Embedded markers distribution [31]. The GelForce sensor has a black shading on the surface of the transparent and flexible silicone body with 40mm height, 90mm length, and 100mm width. Blue and red markers are placed in a depth of 3mm and 6mm respectively. The interval between markers is about 1.5mm.

However, it was named as TACTIP in 2012 [38] for robotic applications. The cross section and the actual TACTIP sensor are shown in Fig. 13a and Fig. 13b respectively. TACTIP mimics the structure of epidermal layers of human skin. By tracking the movements of the internal papillae pins using a camera, deformation can be inferred and computed [38].

In 2019, a new hemispherical dome visuotactile sensor has been developed in Japan [39]. It is like a TACTIP, but has an event-based camera tracking 361 white markers on a black background. The actual picture of the sensor is shown in Fig. 14.

In 2009, Johnson and Adelson from MIT, introduced a new miniature high-resolution pedobarograph-like sensor that converts surface shape and pressure into image and called this device as the retrographic sensor [11]. The whole setup combining retrographic sensor, clear supporting plate, lighting, and camera is known as the GelSight sensor in 2013 [40]. To the best of our knowledge, this is the visuotactile sensor that fuses vision and tactile sensing to a high degree of inter-modal sensing fusion, because it is capable of capturing microscopic surface geometry as small as 2 microns [43] with sensitivity and resolution exceeding that of the human fingertips [44]. It is like a human eye-skin extension device for visual and tactile texture analysis. It can be considered as a visuotactile mirror because it can produce a visual image and a tactile image at the same time.

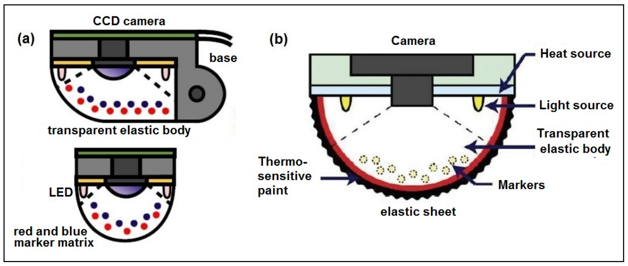

Fig. 11: (a) The configuration diagram of finger-shaped GelForce (2008) [32], and (b) finger-shaped GelForce with thermo-sensitive paint (2011) to sense temperature mimicking a human finger reported [34].

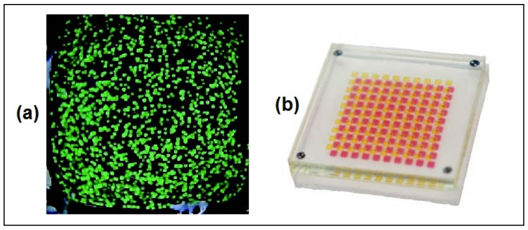

Fig. 12: (a) Fluorescent green spherical markers randomly embedded in the flexible material (2019) [35], and (b) semi-transparent two color dye markers arrange in two layer arrays that overlap to infer tactile forces via subtractive color mixing (2019) [36].

III. THE GELSIGHT SENSOR

GelSight sensor is a miniature high-resolution pedobarograph-like visuotactile sensor invented by Johnson and Adelson in 2009 [11]. Johnson and Adelson introduced their device not as a tactile sensor, but as a retrographic sensor or a 2.5D scanner. The clear elastomeric slab with reflective coating on one side was referred by the inventors as the retrographic sensor because it produces the image of the contacted object on the opposite side of the flexible material. Johnson and Adelson were able to demonstrate how their retrographic sensor can be utilized as a 2.5D scanner to transform surface texture and shape into images. Using photometric stereo algorithm, a high resolution 3D image of microgeometry of the contacted object can be reconstructed using the GelSight sensor. The GelSight sensor has a unique niche of capturing its deformation in response to changing pressure [11]. GelSight sensor can filter out the background of the objects in contact. It can filter out the colors of the object to produce a monochrome image of tactile texture or contour pattern. A textile with different colored patterns, when pressed to the GelSight sensor, will reveal only a

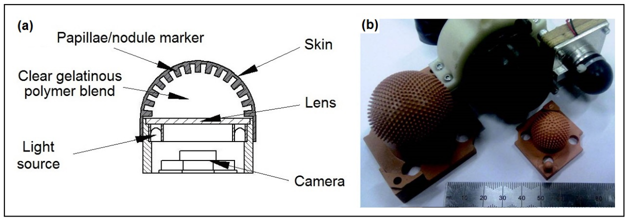

Fig. 13: (a) Cross section of TACTIP, (b) 40-mm and 20-mm TACTIP sensors beside their molds as presented in [38].

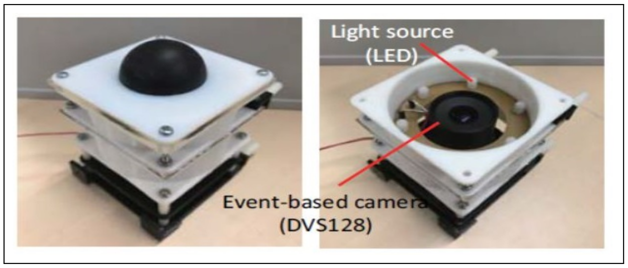

Fig. 14: Hemispherical visuotactile sensor with an event-based camera reported in [39] has a diameter of 40mm.

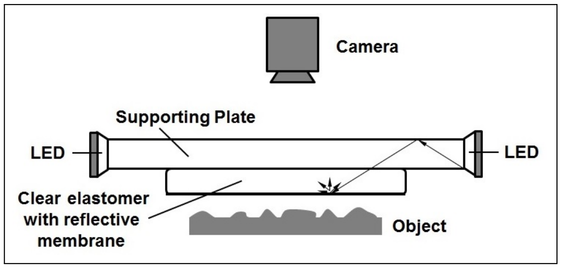

Fig. 15: GelSight sensor structure as reported in [40].

monochrome image of weave pattern. It can filter out the luster of a shiny object like a metallic coin that might be difficult to filter out in image processing alone. GelSight sensor can do instant color and luster image filtering because it has its Bidirectional Reflectance Distribution Function (BRDF) [11]. As an optical sensor, the GelSight sensor can measure the microgeometry of small objects and can be used for 3D image reconstruction. It is like a refreshable mold where the shape and texture of the object pressed to it are revealed on the other side of the reflective paint of the elastomeric slab.

Though the focus of the inventors of GelSight sensor is on the high-resolution 3D image reconstruction for metrology and microgeometry analysis at the time, Johnson and Adelson also reported that the GelSight sensor can be used as a human skin model to study skin and flesh deformation when contacted by object such as clothing, food, and cosmetic products [11]. It can also be used as a tactile sensor in the field robotics to develop a soft fingertip having sensitivity surpassing human skin. This prediction on the GelSight sensor being applied in robotics became a reality in 2014 [41].

IV. GELSIGHT SENSOR HARDWARE

According to Jia et al. [40], GelSight sensor is a visuotactile device that has 4 basic components: 1) clear elastomeric slab with reflective coating on one side, 2) transparent glass or acrylic plate support for the slab, 3) uniform and controlled lighting usually provided by Light Emitting Diodes (LED), and 4) camera or webcam at the back of the supporting plate to capture the impressed image on the slab. There have been many "GelSight" since 2009. However, most of them are retrographic sensors as Johnson and Adelson introduced in 2009. The total package includes the retrographic sensor (1^{st} component) and the other three listed components above as stated by Jia et al. in 2013 [40].

Diagram of the GelSight sensor structure is shown in Fig. 15. The top view and bottom view of the retrographic sensor are shown in Fig. 16a and Fig. 16b respectively. A reconstructed 3D image of the Oreo cookie pressed to the retrographic sensor is shown in Fig. 16c.

The GelSight sensor has evolved from the bulky cubic box structure reported in [11], [42] to a bench configuration [43], portable configuration presented in [43], [44], and desktop configuration [40]. The GelSight sensor was further miniaturized to create a fingertip GelSight sensor to be fitted in a robotic arm. This fingertip GelSight sensor was presented in [41] and was improved in [45]. The new era of GelSight was introduced in 2018 called GelSlim [46] which is a compact design with skin fabric gel covering to make it durable as shown in Fig. 17h. The GelSlim was improved with new a hardware design and better illumination in 2019 called GelSlim 2.0 [47] as shown in Fig. 17i. The different GelSight sensor configurations such as the cubic box, bench, portable, desktop, finger, fingertip, improved fingertip, GelSlim, and GelSlim 2.0 are shown in Fig. 17.

A. Retrographic sensor

Retrographic sensor is the term used by Johnson et al. [11], [43] describing the first component of the GelSight sensor reported by Jia et al. in [40]. It is made of a clear elastomeric slab with a reflective coating on one side as shown in Fig. 16a and Fig. 16b. It is like an optical filter that only shows the relief geometry of the contacted object. More detailed discussion on the clear elastomer and reflective coating are as follows:

1) Clear Elastomeric Slab:

Optical transparency, robustness, hardness, stretchability, and complexity to fabricate are some factors to be considered in choosing the elastomer base [42]. Current GelSight elastomers are created in the laboratory by using thermoplastic elastomer (TPE) which requires oven to melt in a mold or silicones made by two separate liquid parts that form a firm gel when mixed [48]. Three major challenges in creating a clear elastomer are the long curing time of about six to seven hours [48], quality consistency [49], and the formation of air bubbles within a gel that needs vacuum pump for degassing [48]–[51]. Aside from these challenges in creating clear elastomer in the lab, according to [52], the GelSight might have an impressive spatial resolution (30-100 microns), but the elastomer can be easily damaged during grasping thus requires frequent

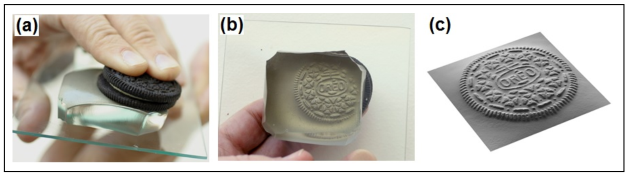

Fig. 16: Retrographic sensor [11]. This is a clear flexible material with a reflective coating. (a) Oreo cookie is pressed to the sensor, (b) retrographic image can be seen on the other side of the sensor, and (c) reconstructed 3D image.

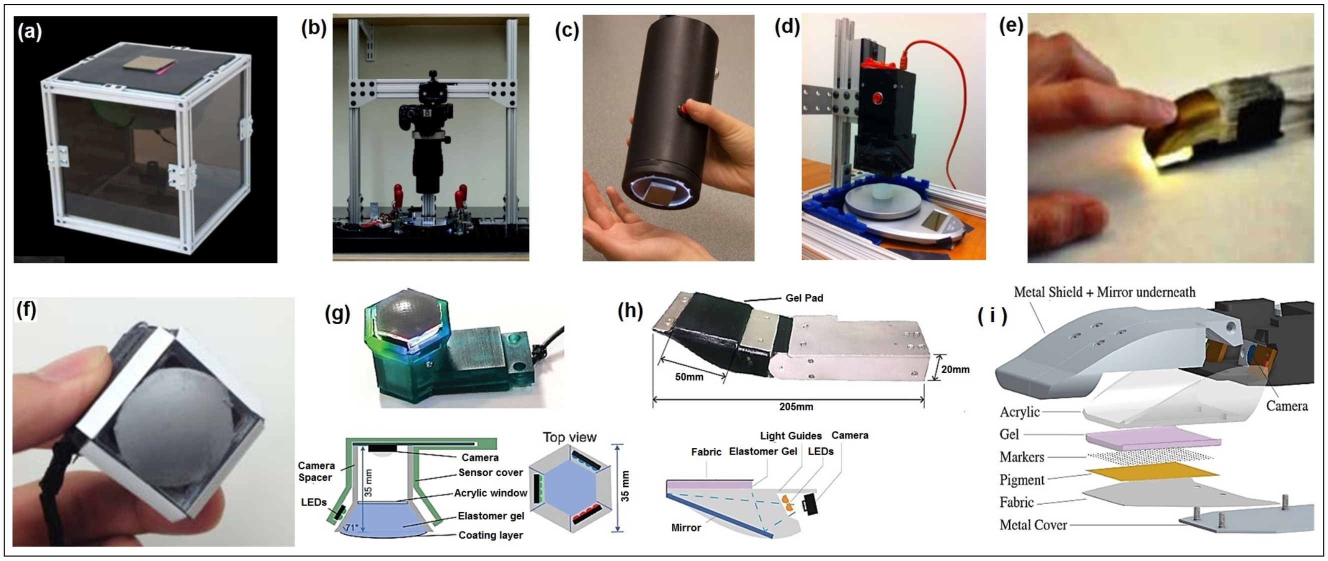

Fig. 17: Evolution of GelSight sensor configurations: (a) Cubic box (2009): side=30cm, retrographic sensor (60mm x 40mm). LED: red(R), green(G), blue(B). Camera: DSLR [11], [42], (b) Bench (2011): Retrographic sensor is on a circular glass plate (5.5in. dia., 0.5in. thick), LED: 6 (RGB) equally spaced on its side [43], (c) Portable (2011): acrylic tube (3-in. dia., 8-in. long). Retrographic sensor is on a glass plate (2.25in. dia. and 0.25in. thick) at end of the tube. Camera: 0.8MP Point Grey Flea2 [43], (d) Desktop (2013): similar to portable but with rectangular housing (62mm x 62mm x 150mm) [40], (e) Finger (2013): picture was introduced in [44] (f) Fingertip (2014): cube side=3cm. LED: (RGB, white). Camera: Logitech 310 [41], (g) Improved fingertip (2017): 3D printed frame, hexagonal face (35mm diagonals and 35mm height). LEDs: RGB. Camera: Logitech 310 [42], [45], (h) GelSlim (2018): A compact design with slant mirror inside and skin fabric gel covering. LED: only white. [46], and (i) GelSlim 2.0 (2019) improved GelSlim sensor with permanent markers, LED: red and green on the sides with RaspPi Spy Camera [47].

maintenance. According to Abad et al. [53], we can replicate the GelSight sensor using Commercial-Off-The-Shelf (COTS) clear silicone cosmetic sponge as shown in Fig. 18. Hardness of GelSight sensor elastomer has typically Shore A values between 5 and 20 and could be varied according to different applications [42]. Shore A values of COTS silicone sponges reported in [53] are 2.5 and 7.

2) *Reflective coating:*

The reflective coating of the GelSight sensor is like a flexible mirror reported in [16] which reflects the relief or profile of the object pressed into the sensor. A thin layer of silicone mixed with pigment painted on one side of clear elastomer acts as the reflective coating [42]. COTS spray paints cannot be used as reported in [53] because they do not stick properly on silicone and will crack eventually when pressed. Semi-specular and matte coatings for the GelSight sensor as reported in [42] are shown in Fig. 19. According to Yuan et al. [42], microgeometry on the surface normal can be captured by semi-specular coating while general shapes can be acquired and measured accurately using matte coating.

3) *Markers on reflective coating:*

The introduction of markers to the flexible part of a visuotactile sensor dates back to 1966 [16]. Permanent markers in the form of dots or triangles on the reflective coating of GelSight sensor were introduced by Yuan in 2014 [48]. Normal force, shear force, and slip can be deduced from the motion of the markers [42], [48]. GelSight sensor's permanent markers can be printed in a dense quasi-random triangular pattern or a grid-like formation using a stencil pattern or transfer paper as reported in [48]. Grid dots were also introduced in GelSlim 2.0 [47].

GelSight sensor used in sensing, recognizing, and measuring surface texture [11], [44] and microgeometry [43], lump detection [40], manipulation and localization of small parts [41], and tactile mapping and localization [54] do not have the permanent markers. Research related to measurement of force, shear, slip, [42], [45], [55]–[58] and hardness estimation [59] have used the GelSight sensor with permanent markers. According to Yuan et al. [55], higher precision displacement field can be achieved by increasing the density of markers, but this will affect the GelSight's capability to measure a height map. Dong et al. reported in [45] that a GelSight sensor with permanent markers can be used to measure geometry through photometric stereo algorithm and measure slip through the tracking of permanent markers using the improved fingertip GelSight sensor configuration. But the introduction of permanent markers in the reflective coating of GelSight sensor might obscure some important image features that might be helpful for object recognition through 2D image processing such as in textile type recognition based on weave patterns.

Two GelSight-like sensors [60] and [61] reported the need for a unified visuotactile sensor in the field of robotics especially in the manipulation of small objects. In small object manipulation, there is a need to recognize shape and orientation through image features and at the same time measure the applied force in the gripping of the object. The FingerVision

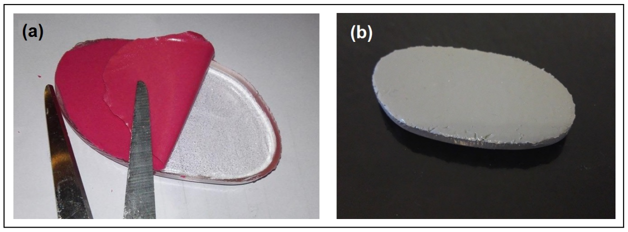

Fig. 18: Commercially available silicone cosmetic sponge can be used to replicate the GelSight sensor as reported in [53]: (a) silicone sponge with pink cushion; pink cushion can be easily removed by cutting the edges of the sponge, and b)the silicone sponge painted with a reflective coating on one side.

sensor introduced in 2016 [51], [60] has permanent markers for tracking the deformation of the flexible membrane, but it has no reflective coating to differentiate the movement of the contacted object from its background. It was claimed in [51], [60] that the FingerVision sensor has rich information due to the transparent sensor. It was utilized to monitor the change in the background of the contacted object. Another FingerVision is reported in [62] which has a similar reflective coating as the GelSight sensor but uses a fisheye camera. Furthermore, small object manipulation and orientation with tactile sensing using one visuotactile device was reported in 2018 [61], but the tactile analysis is based on only four markers. The high resolution of the visual texture image is comparable to the GelSight sensor, but it has no tactile markers in the middle of the sensor that can track the deformation in the reflective coating at it touches the object. The displacement field markers density is not comparable to the GelSight sensor.

B. Transparent plate support

Clear transparent glass plate or acrylic plate has been used to support the elastomeric slab in a GelSight sensor and has been used as light waveguide to diffuse light through TIR. Glass plate has been used in early GelSight sensors [11], [40], [43], [44], while the new sensor versions such as fingertip GelSight and GelSlim used acrylic plate as the supporting base and light waveguide [41], [46], [47].

C. Lighting

Uniform and controlled lighting condition is necessary to illuminate the elastomeric slab. GelSight sensor lighting can be single or multicolored lighting. Light-emitting diodes (LED) are used in the GelSight sensor. Aside from GelSlim [46] which uses two neutral white, high-powered, and surface-mount LEDs (OSLON SSL 80) on each side of the finger, all the other GelSight sensor structures have multicolored lighting.

Multicolored lighting has been used for 3D image reconstruction. Multicolor LEDs positioned at different locations are needed for photometric stereo technique. According to Yuan [48], different LEDs with different colors mounted at different positions around the slab are required to detect the surface normal in R^3 space. Moreover, Yuan discussed that using photometry stereo technique, impressed image on the reflective coating of the elastomeric slab can be reconstructed in 3D using differentiated illumination direction. There are two ways to get differentiated illumination direction: 1) switching different LEDs positioned at different locations and take separate pictures of the same scene, and 2) using multi-color LEDs simultaneously and take a single picture; the reflection of different color LEDs can be known by taking different channels of the color image.

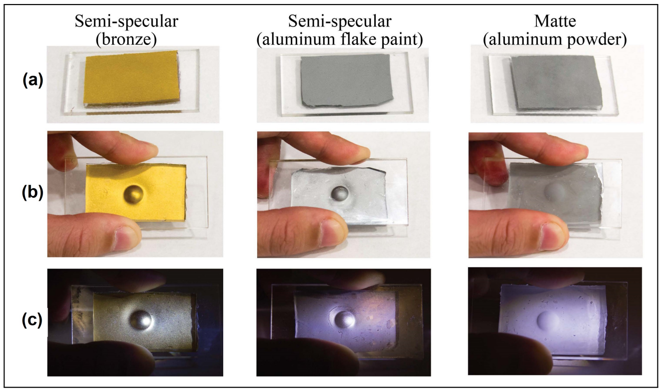

Fig. 19: GelSight sensor coatings: microgeometry on the surface normal can be captured by semi-specular coating while matte coating is suitable for measuring general shapes as reported in [42]. (a) Outside view, (b) Inside view, and (c) Inside view, light from side.

In addition to the multicolor LEDs 3D image reconstruction, a new form of lighting has been introduced by Abad et al. [53] using the UV light. UV LEDs are needed to show the presence of UV markings in the reflective coating as discussed in the previous section. UV markings can be turned on or off using UV LEDs.

D. Camera

With the use of a digital camera, the retrographic image on the reflective skin of GelSight sensor can be captured and recorded. Aside from still images, a digital camera can also be used to record videos, for example measuring pulse-rate [63].

The first GelSight sensor [11] used Canon DSLR (EOS-1D Mark III) with 100mm macro lens, 40cm away from the sensing element. The bench configuration GelSight sensor used an 18 MP Canon EOS Rebel T2i camera with macro lens MP-E 65mm installed vertically while the portable configuration used a 0.8 MP Point Grey Flea2 camera [43].

With the miniaturization of the GelSight sensor, Logitech C310 which has 5 MP resolution has been used by the fingertip size configuration [41]. Logitech C270 with 3 MP resolution has been used by [53]. Although it has been stated in Logitech website that both Logitech webcams have fixed focus, the webcam lens can be manually adjusted by opening the case and rotating the lens [64] to have a clear image at a shorter distance. Aside from webcam, another small digital camera known as Raspberry Pi Spy Camera was used in GelSlim configuration [46].

V. GelSight Sensor Software

The data gathered by the GelSight sensor are stored in images. The captured image from the GelSight sensor can be a retrographic image or a tactile image. The retrographic image is the image of the deformation of the elastomeric slab with reflective coating captured by the camera on the reverse side of the slab. This is a 2D relief geometry-image of the pressure points or the contact area between the object and the GelSight sensor. In a general sense, we can say that the retrographic image is for visual texture analysis, microgeometry, shape measurement, 3D image reconstruction, object recognition, and object classification. On the other hand, we define the tactile image captured by the GelSight sensor as a retrographic image with dot markers. As stated in the previous section, information about shear force, normal force, and slip can be deduced from the motion of the markers [42], [48].

Different GelSight sensor image processing algorithms were reported in [11], [40], [41], [43], [44], [48]. A 3D image reconstruction algorithm known as photometric stereo algorithm was applied to the retrographic images in 2009 [11]. The reconstruction algorithm was improved in [43] to accurately capture shallow microgeometry with high efficiency regardless of how the material scatters light. Through the photometric stereo algorithm, the measurement of surface texture and shape as well as microgeometry capture were accomplished. Aside from photometric stereo algorithm, sensing and recognizing surface textures can be achieved using Local Binary Patterns (LBP) enhanced with multi-scale pyramid and Hellinger distance metric as reported in [44]. Furthermore, standard Support Vector Machine (SVM) classifier with a supervised learning algorithm has been used for lump detection as reported in [40].

Reporting more on algorithm, the fingertip GelSight sensor in [41] used Binary Robust Invariant Scalable Keypoints (BRISK) [65] algorithm that finds robust keypoints with binary descriptors and feature-based RANdom SAmple Consensus (RANSAC) [66] operating on a height-map produced by photometric stereo algorithm to create tactile maps and to localize tactile information within a map.

The GelSight sensor with dot markers in [48] used optical flow algorithm [67] based on Lucas-Kanade (LK) [68], [69] for analyzing of the motion of image features. An image segmentation, and tracking of centroids of the markers have also been applied to GelSight sensor with markers. With the use of tracking-surface-marker method presented in [55], partial slip during the shear loading can be inferred from the displacement field of the flexible material.

Deep learning algorithms such as Convolutional Neural Network (CNN) and Recurrent Neural Network (RNN) were introduced to the GelSight sensor in 2017 [70]. According to Yuan et al. [71], the success of computer vision has been greatly accelerated through the use of deep learning. CNN was used in many GelSight studies related to object recognition and classification as well as cross-modal analysis as reported in [54], [56], [70]–[79].

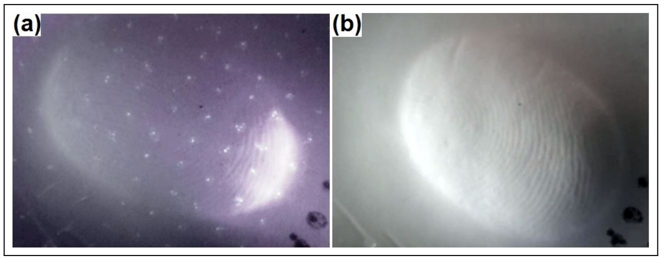

Fig. 20: A switchable ultraviolet (UV) markers: (a) UV markers on, and (b) UV markers off. The use of UV markers has been proposed in [53].

VI. Discussion, Application, and Future Development

This review paper presents a wide range of literature related to visuotactile sensors with emphasis on GelSight sensor. The authors' opinion is that GelSight sensor is an ideal visuotactile sensor because of its high spatial resolution in vision [43] and high sensitivity in tactile [44]. It has proven its worth in a wide range of applications from haptics, robotics, and computer vision.

Visuotactile sensors have been used since 1960's, from the pedobarograph sensor to the current GelSight sensor. However, earlier versions focused on external structure modificaton of the flexible material such as reflective skin, paint, markers, and flexible mirror. The development of visuotactile sensors moved to another level towards internal structure modification. For example are GelForce sensor (2001) with red and blue beads inside [29], the sensor of Sferrazza et al. (2019) with fluorescent green spherical markers [35], and the sensor of Lin and Wiertlewski (2019) with semi-transparent colored markers (dye) arranged in an overlapping double array [36].

With the introduction of permanent markers, GelSight sensor seems to be treated as two separate sensors: without markers and with markers. From the point of view of image processing, permanent makers can be treated as image features that can help in analyzing force, shear, and slip or can be considered as unnecessary in microgeometry and 3D image reconstruction, object recognition, object classification, and shape measurement [42]. However, permanent markers might be treated as noise that negatively affects some important 2D image features especially if these markers are bigger than the image features [42]. Moreover, increasing the density of markers affects the capability of the GelSight sensor to measure height map [55]. The issue that markers can be a noise and might obscure patterns in 2D images can be observed in the images presented in [72]–[74] where the GelSight sensor with permanent dot markings was used in cloth or textile characterization. The use of two kinds of GelSight sensors with and without markers are presented in [77].

In our previous work, we introduced GelSight sensor with UV markings that can be visible only when UV light is on [53]. Therefore, UV markers can be turned off in microgeometry and shape measurement, object recognition, and object classification studies. The comparison of fingerprint with UV light on and off states are shown in Fig. 20a and Fig. 20b

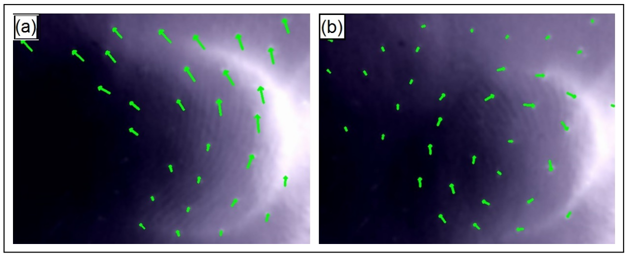

Fig. 21: Tracking the UV markers: (a) UV markers are detected by optical flow algorithm and the direction of fingertip twisting is shown by a swirl in counterclockwise, and (b) clockwise direction.

respectively.

However, UV markers can be on, when the magnitude and direction of fingertip movement is studied as shown in Fig. 21. Here, UV markers detected by optical flow algorithm and the direction of fingertip twisting is shown by a swirl in anticlockwise and clockwise direction as shown in Fig. 21a and Fig. 21b respectively.

The miniaturized finger GelSight [44] and GelSlim [46] were reported in 2013 and 2018 respectively. The shape, size, and placement of a flexible medium for sensing is comparable to the human-fingertip-like visuotacile sensor developed in 2000 [28]. If that is the case, miniaturized finger GelSight and GelSlim would be useful in many robotics exploration, and manipulation applications in the future.

Haptic primary colors consist of force, vibration, and temperature [80], [81]. GelSight sensor would be an ideal for many applications to have switchable UV markers, and thermo-sensitive paint as the reflective coating to measure force and temperature respectively. Moreover, it has been reported that GelSight sensor is reliable enough to measure human's pulse [63]. Therefore, possible improvement would be carried out on how to use very compact, unified, and optimized GelSight sensor with switchable UV markers and thermo-sensitive paint as reflective coating to measure different vibrations. In this review paper, the authors would bring the attention for miniaturized futuristic GelSight sensor with vibration and temperature measurements that could be useful in smart exploration and manipulation in robotics, medical applications, and space exploration in the near future.

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