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A highly sensitive 3D-shaped tactile sensor

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***Abstract*—In this paper we introduce a novel way of producing highly sensitive 3D-shaped tactile sensors. The sense of touch is critical for enabling humans to master intricate manual interactions. Numerous anthropomorphic robots make extensive use of complex three dimensional body parts in mimicry of their biological counterparts. We use laser structuring technology to augment freeform surfaces with conductive tracks, paving the way for the manufacturing of 3D-shaped tactile sensors. The signal acquisition electronics can be effortlessly embedded on the backside of an artificial layer of skin. We evaluate the performance of the sensor and discuss the results in detail.**

As an exciting application, we produced a tactile fingertip sensor for the Shadow Robot Hand that incorporates 12 tactile sensor regions and the embedded signal acquisition electronics. The integrated microcontroller is able to capture force patterns with a frame-rate of more than 1 kHz, allowing object slippage to be detected.

I. Introduction

The importance of human tactile sensing in successful grasping and manipulation was vividly demonstrated in an early experiment by Westling and Johannson [1]. They anesthetized the skin of the hands of volunteers and thus deactivated their tactile receptors, which revealed great difficulties while they tried to maintain stable object grasps.

We argue that equipping robotic hands with human-like tactile sensing capabilities, along with a fundamental understanding of motor-control processes will eventually lead to universal dexterous robotic hands capable of matching, or possibly even exceeding, human manual intelligence [2]. Towards this end, we have captured and analyzed human bimanual interaction data in our Manual Intelligence Laboratory [3] using motion tracking, posture and tactile datagloves [4], [5] and tactile-sensitive objects in the shape of a soda can [6] and a book [7]. These and similar experiments deepen our understanding of human manual operations and enable us to realize more sophisticated manual control strategies for robot hands. As an example, we have demonstrated the benefits of mimicking humans in robotic manipulation by applying the gathered knowledge to the task of opening a jar with the Shadow Robot Hands [8]. In experiments such as these, we have found that a lack of tactile feedback is the most detrimental handicap in our quest to conquer more complex manipulation tasks.

Adding the sense of touch to robotic hands has been previously investigated. In an early paper, Butterfaß et al. [9] introduced the four-fingered DLR Hand II, which is approximately twice the size of an adult human hand, and has single 6D force/torque sensors located in each fingertip. A single sensor has the drawback that all of the forces in its area of coverage are summed leading to the loss of potentially important spatial force information. Robotic hands that use tactile sensor matrices are able to capture finer grained contact location and force amplitude data. Oddo et al. [10] demonstrated a 2×2 MEMS-based strain-gauge sensor sized like a human fingertip. Due to the required (relatively) complicated signal conditioning electronics and limited available space inside the finger joints, the addition of further tactile cells (tactels) into the fingertip was not achievable. An interesting approach that succeeded in attaining a high sensor density by using inductive coils embedded in the finger flesh was recently demonstrated by Wattanasarn et al. [11]. However, their approach also suffers from the necessity to have complicated electronics for each single tactel. In a different approach, Ohka et al. [12] demonstrated an optical tactile fingertip sensor with more than twice the size of a human fingertip. Computer vision algorithms were applied to the images captured by a fiberscope. The lack of a compact embedded design and the need to sacrifice the majority of

Fig. 1. Resistive fingertip tactile sensor in anthropomorphic 3D shape with 12 tactile cells and embedded signal processing electronics for human sized dexterous robotic hand. (Note that the cutout in the sensor material shielding the electrodes is only for illustration purposes.)

the available space in the fingertips in order to capture an unobstructed field-of-view are two major drawbacks of their design.

Resistive and capacitive tactile sensors require typically much simpler signal conditioning and can thus be produced with relative ease in higher tactel counts. Often in these sensors, printed circuit boards (PCBs) are used as sensor electrodes [13]–[15]. Using flexible substrates, such as kapton instead of fiberglass, which is commonly used in rigid PCBs, tactile sensors having flexibility in a single dimension can be built [16], [17]. With a clever design that cuts the flex print PCB, tactile sensors capable of covering two-dimensional surfaces with limited radii have also been demonstrated [18], [19].

In a recent paper, Wettels and Loeb demonstrated a multimodal fingertip sensor capable of sensing thermal flux, microvibration and force [20]. The performance of the sensor is impressive, but due to the electronic circuitry extending (in a rigid manner) deep into the middle phalange of the fingers, joint movement between distal and middle phalanges is eliminated.

To overcome all these drawbacks, we have developed a compact tactile sensor with embedded electronics using a laser structuring process. This process can be applied to almost arbitrarily shaped surfaces, allowing tactile sensing to be added to object surfaces previously not possible. In the next section we introduce our free-form shaped tactile sensor design and describe its construction steps in detail. Sec. III demonstrates an innovative application for the developed sensor in the form of a compact embedded robotic fingertip [Fig. 1]. In Sec. IV the sensor performance is evaluated and measurement results are given. Finally, Sec. V summarizes the paper and discusses future work.

II. Tactile Sensor Design

Our tactile sensor, designed for free-form surfaces, is based on a resistive working principle in which the interface resistivity between two surfaces changes according to the applied load. This is achieved using conductive tracks as electrodes and conductive foam or rubber as the sensor material, which is a technique first introduced by Weiss and Wörn in [21]. Fig. 2 illustrates this basic working principle and depicts the three parts that contribute to the sum of the final sensor resistance, R_t. These are the variable contact interface resistances, R_{s1} and R_{s2}, and a constant sensor material volume resistance, R_v. In its simplest form, such a tactile sensor can be produced by using a common printed circuit board (PCB). A number of possible sensor materials can be considered, such as elastomer foam with added carbon particles (as used in typical ESD-packaging foam), conductive fabrics, and conductive rubber [22]. Using flex print PCB instead of a rigid board, tactile sensors, deformable up to a limited radius, can be produced.

The present work extends this basic resistive tactile sensor by allowing the sensor to be manufactured in almost arbitrary 3D free-form shapes. To produce 3D-shaped electrodes we use the Laser-Direct-Structuring (LDS) process, described in detail in the next section. To produce free-form sensor material, we use high-speed milling of conductive elastomer foam in combination with vacuum clamping.

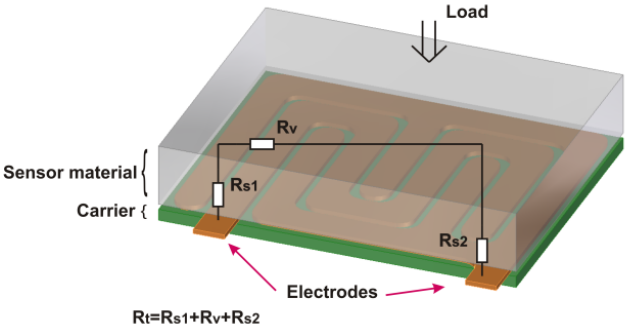


Fig. 2. The resistance of a single resistive tactile sensor cell, measured between two electrodes, is the sum of sensor material volume resistance and contact resistances between the sensor material and the electrodes. The contact resistance changes according to the applied load on the sensor foam.

A. Laser Direct Structuring

The Laser-Direct-Structuring process, developed by LPKF Laser & Electronics AG in the late 1990's, allows circuit layouts to be produced on complex three dimensional carriers, also called Molded-Interconnect-Devices (MIDs) [23]. With LDS, the laser beam structures the desired pattern directly onto the (complex) plastic piece. At least two other methods are available for creating MIDs: multi-component injection molding and hot stamping. However, both have considerably higher manufacturing costs, especially unviable in smaller production runs, due to additional required specific mold tools needed to create the circuit on the piece. Another considerable benefit of the LDS method is the possibility of creating very fine structures, down to 100μm.

The production of tactile sensor electrodes with LDS technology is a five-step process. The first step is to choose a material for the plastic carrier, which narrows some of the design parameters for later laser structuring. A number of laser-activatable thermoplastics are available, differing not only in mechanical properties such as density, tensile modulus or melting temperature, but also in their LDS process parameters, such as the method for creating vias (through-hole connections). We have chosen Ticona's Vectra E840i LDS liquid crystal polymer thermoplastic material, due to its excellent dimensional and thermal stability, and its unique property of allowing very tiny vias to be directly punched by laser during the structuring process. As the second step towards LDS MID, a one component injection mold for the required 3D-shaped form must be constructed and produced. After the tools are ready, the dried and pre-heated plastic granulate is injected under high pressure into the mold, where the MID-blanks can be extracted after the cooling phase. In the third step, the blanks are structured with a laser. The laser-activatable thermoplastic contains a special additive in

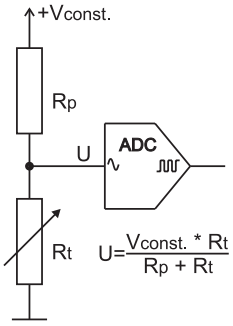


Fig. 3. The varying tactel resistance R_t is digitized with a voltage divider circuitry with a constant pull-up R_p and an analogue-to-digital-converter (ADC). The two pins of R_t form the electrodes of a tactile cell.

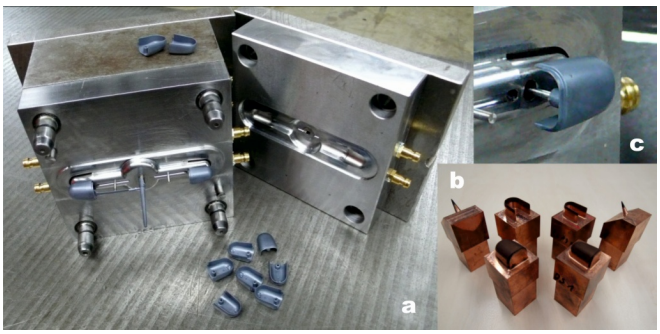


Fig. 4. (a) Single shot, two-plate injection mold for fingertip MID. By turning the sprue bush 180°, the mold can be selectively used to produce fingertip MIDs or the slightly larger thumb-tip MIDs. (b) Copper electrodes for electric discharge machining, used for achieving the required surface quality of the mold. (c) Injected fingertip blank.

the form of an organic metal complex, which is activated by a physical-chemical reaction induced by the focused laser beam. This cracks open the complex compounds in the doped plastic, and breaks off the metal atoms from the organic ligands. These act as nuclei for subsequent chemical copper coating. For our tactile sensor electrodes we have chosen an interwoven M-shaped electrode track that provides highest sensitivity to first touch as previous experiments have shown [15]. In the fourth step, the activated MID's are treated in a number of sequential chemical baths, such as a cleaning bath to remove laser debris, an additive built-up bath to add copper, and a bath for chemically adding a thin, final layer of gold to avoid oxidation. In the fifth and final step, the electronic components, such as the data acquisition electronics, are soldered directly to the LDS-MID's, making the final design extremely compact and robust.

B. Signal digitalization

The resistance measured between two electrodes, or an electrode and a common ground-plane shared by all tactels of a sensor array, is converted to voltage with a simple constant pull-up resistor attached to a constant power supply (voltage divider circuit) [Fig. 3]. The voltage at the junction of the resistors can be sampled by an analog-to-digital converter (ADC), which provides the data in a digital form for transmission or further signal processing. Altering the value of the pull-up resistor allows us to shift the measurement range. Higher resistance allows lower pressures to be measured, at the cost of inducing a higher signal noise and limiting the maximum measurable force.

III. Fingertip Sensor for Artificial Hand

Our tactile sensor technology is ideal for fingertips, which play a crucial role in human grasping and manipulation and have the highest spatial resolution of the tactile sense in humans [24], [25]. The tactile sensor is not only usable for dexterous anthropomorphic robotic hands, but also for hand prostheses that allow patients regain a sense of touch and thus considerably improve their abilities.

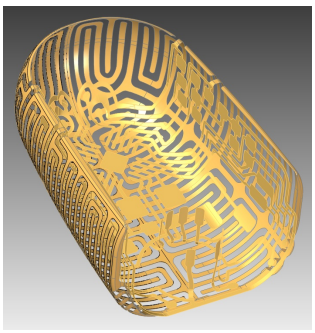
The size of the developed fingertip sensor was chosen to match that of the fingers in the Shadow Robot Hand[1], which are approximately the size of adult human fingers. Numerous hand prostheses are also created using similarly sized fingers, such as RSL-Steeper's BeBionic[2] or Otto-Bock's Michelangelo[3] hands.

A. Fingertip sensor construction

The LDS process allows us to embed tactile sensor electrodes and the printed circuit board into a single 3D shaped plastic part. During the shape design process, four basic constraints had to be considered: a) the ability to manufacture the form with an injection mold, b) electrode tracks could not be placed under the mold ejectors, c) maximum material depth was limited to 0.2mm in via locations (to allow the laser to punch a hole through it), and d) access to all desired conductive tracks for the laser beam had to be ensured. The last restriction is less rigorous, as the laser beam is allowed to hit the material with an angle of up to 75° w.r.t. the surface normal. The areas of the parting lines of the injection mold need to have a very high quality to avoid burrs that can cause cracks in the conductive tracks if they cross these areas on the final part. As recommended by the plastic granulate manufacturer, we used 1.2343 electroslag remelting cavity plates, eroded to a surface roughness of R_a 0.4μm (extremely smooth), to achieve a reliable LDS process [Fig. 4]. To provide sturdy mechanical fingertip attachment, our design embeds a mounting dome with a threaded hole directly in the MID carrier, limiting the required component count to a minimum.

In contrast to common electronic PCBs, the design of the tracks with 3D-shaped MIDs also has to be developed in 3D. Fig. 5a displays the result of the 3D-CAD-circuit-design, with the tracks of the tactile sensor electrodes on the outside and the tracks for the attachment of Surface-Mount-Devices (SMDs) on the inside of the fingertip MID. Fig. 5b shows the

[1]http://www.shadowrobot.com/
[2]http://bebionic.com/
[3]http://www.ottobock.at/



(a) CAD screenshot of constructed 3D-shaped tracks.

(b) Finished fingertip after laser-process and chemical baths. The upper right inset shows the CNC-milled 3D-shaped sensor foam with mounting bracket.

Fig. 5. The tactile sensor electrodes and electronic interconnects, produced with the Laser-Direct-Structuring process. The tracks on the outside of the fingertip form the 3D-shaped tactile sensor electrodes; the inside tracks form the 3D printed circuit board to solder Surface-Mount-Devices (SMD) for data acquisition and processing.

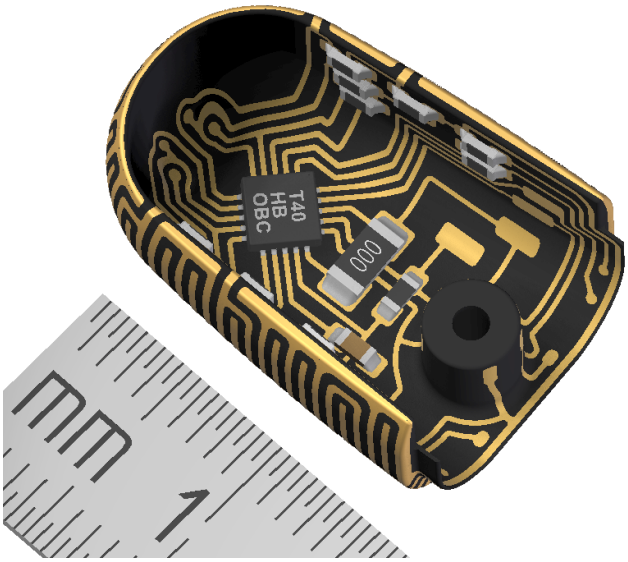


Fig. 6. The LDS process allows data acquisition electronics to be directly embedded on the backside of the sensor. A metric ruler is displayed for size comparison.

finished fingertip MID after laser structuring and chemical baths.

To produce the required 3D-shaped sensor material that covers the electrodes, we use a conductive elastomer from Weiss Robotics. Thanks to a relatively high ductility, this material can be produced in the desired shape using a high-speed mill. Milling the foam is a two-step process. First, the outer shape is milled on a flat vacuum table, followed by milling the inner cavity in a negative vacuum to form the outer shape. Our design uses uniform sensor foam thickness of 2.0mm, a minimal thickness we were able to reliably manufacture. The milled sensor foam is glued to a plastic bracket, keeping the foam within the limits of the desired clearance to the electrodes [inset of Fig. 5b]. The tactile fingertip sensor is mounted onto the robotic hand using a screw, allowing a firm fit of the bracket and the MID.

B. Data acquisition

Although we explicitly targeted the fingertip of the Shadow Robot Hand, the manufacturing steps and the developed data acquisition electronics can be used with no or very minimal alterations to build tactile fingertip sensors for numerous other robotic or prosthetic hands. In the Shadow Robot Hand, the fingertips are provided with +5VDC and are connected with a 2 MHz SPI bus to the main control board of the hardware. These are the main limiting factors for our data acquisition scheme – in addition to the very confined space that is available. For an improved signal-to-noise ratio and due to the availability of the digital bus, the circuitry for analog voltage measurements and the digital communication was directly integrated into the fingertip. Instead of relying on a stock ADC with an integrated SPI-bus, we decided to use a programmable module in the fingertip for higher protocol configurability and thus better adaptability to different hardware systems.

While grasping and manipulating, humans can detect object slippage using Pacinian corpuscles – mechanoreceptors in the human skin, capable of registering vibrations up to 400 Hz [25]. In our previous research concerning flat tactile sensor arrays, we showed that slip detection is possible with our sensor design employing high sampling rates around or above 1 kHz [26]. Hence, a major design goal was to maintain or improve on this capability.

From these considerations a single reprogrammable microcontroller chip was chosen to perform both the analog sampling and the digital communication. The microcontroller used is an 8-bit ATtiny40 in a 3×3mm QFN package. Using an internal 8 MHz clock, this chip needs only one capacitor and a resistor (as external components) to operate. It features 12 ADC inputs with a sampling resolution of 10 bits and a maximum combined sampling frequency of 40 kHz. It enables our fingertip sensor to be equipped with 12 tactels, resulting in an average spatial resolution of ≈5.5mm. In terms of digital communication it is employed as a slave device with an SPI clock rate of up to 2 MHz. As the electrical components are fitted in the inside of the fingertip, the electrodes on the outside have vias to connect to the ADC channels of the microcontroller [Fig. 6]. Additionally a dedicated pull-up resistor is connected between each tactel and the supply voltage of +5V.

IV. Sensor Evaluation

To evaluate the performance of the tactile sensors, we use a custom built measurement bench capable of exerting forces from 0N to 80N [Fig. 7]. The reference force is measured by a calibrated industrial strain gauge force sensor connected to a signal amplifier. The strain gauge sensor is mounted on a vertical linear axis and its position is actuated by a stepper

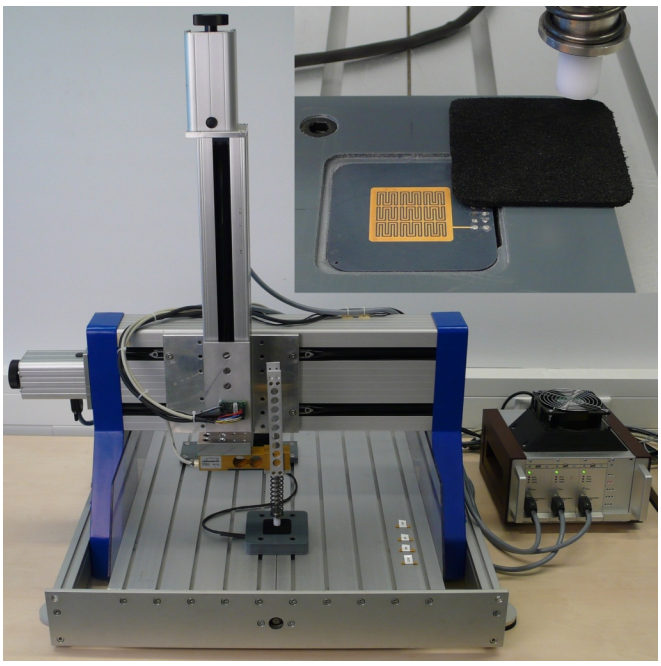


Fig. 7. The sensor performance was evaluated with a custom built measurement rig with a calibrated industrial strain gauge reference sensor mounted on a numerically controlled linear axis. The upper right inset shows a close-up of the 3×3 flat tactile sensor (produced with LDS-technology for benchmarking purposes), the conductive sensor foam, and the circular probe.

motor driven by the connected PC. The linear movement is transformed to a change in force via a coil-spring. To test the tactile sensor introduced in this paper, we used a circular plastic (POM) probe tip with 1 cm^2 tip area. Measurements were done using flat probes on a flat tactile sensor specimen, considerably simplifying the experimental setup in regards to freeform specimens. As the sensor array output depends only on the applied force and the contact surface area, no error to measurement results was expected due to this simplification. As sensor material we used a conductive foam from Weiss Robotics with a milled thickness of 2.0 mm. Each tactel of the sensor was connected via an exchangeable pull-up resistor to a regulated +5V voltage source. The selection of the pull-up resistor value allows shifting the force region of interest as demonstrated in the results of the measurements. The voltage drop over the sensor, the supply voltage and the strain-gauge reference value were sampled with a 16-bit DAQ-card. We limited our measurements to an upper value of 10N, as a recent experiment has shown that human finger forces are limited to this value [27].

During the measurement trials we loaded the sensor from idle to 10N and retracted the probe tip back to idle again. For this, we positioned the probe above the measured tactel and iteratively moved the probe tip downwards in steps of 0.1 mm. At each step we waited for 0.3 seconds for the mechanics to stabilize and performed simultaneous measurements of the test sensor and the reference strain gauge sensor. We continued until a force of 10N was produced, after which we retracted the probe tip in the same fashion to produce

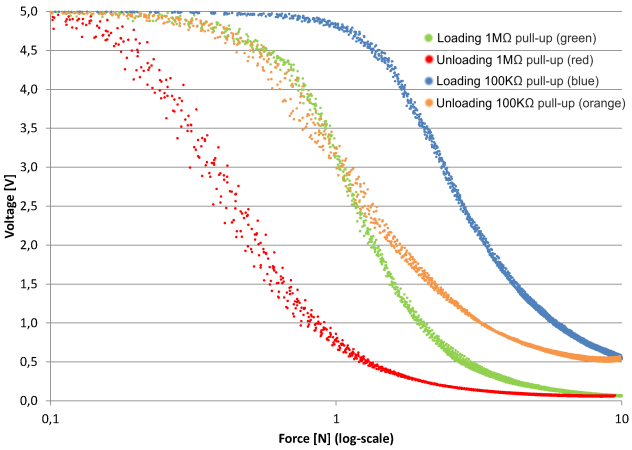


Fig. 8. The sensor output as measured using 1cm^2 plastic (POM) flat probe tip using 100KΩ and 1MΩ pull-up resistor values, while the voltage divider circuit supply was constant 5V. Green and blue points depict the loading phase from idle to 10N, the red and orange curves show the measured points captured during the unloading phase. Each trial was repeated 10 times.

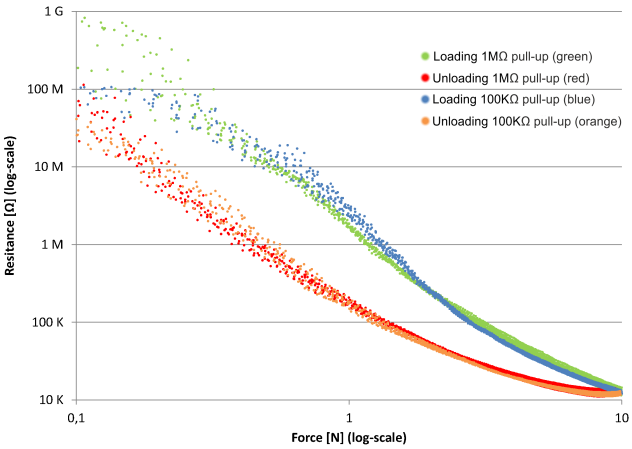


Fig. 9. The calculated resistance of the tactile sensor from the input data of Fig. 8. 0.03N was experimentally found as reliable detection threshold using 1 cm^2 probe tip and 1MΩ pull-up resistor.

measurements in both the positive and negative directions. Over 500 data points were gathered in a single trial, lasting approximately 6.5 minutes. Fig. 8 depicts the sensor output over 10 consecutive trials for two pull-up resistor values – 100kΩ and 1MΩ. Noticeable hysteresis in the sensor output can be observed and is found in many tactile sensors [28]. Higher pull-up resistor values shift the measurable force range towards lower forces thus making the sensor more sensitive, but also limiting the maximum discriminable force.

Fig. 9 displays the calculated sensor resistance. The sensor is highly sensitive to first touch (with 1MΩ pull-up resistor, reliable detection of 0.03N/cm^2 was demonstrated) and the signal repeatability is very high.

V. Conclusions and Future Work

In this paper we introduced a novel tactile sensor technology for creating arbitrary 3D-shaped force-sensitive surfaces. The construction of the sensor was presented in detail and quantitative results were given. As a novel application, we presented a multi-tactel fingertip sensor, with a size equal to a typical adult male fingertip, with embedded data acquisition electronics and capable of very high sampling speeds of over 1 kHz. The designed fingertip was built for dexterous robotic hands, allowing feedback during grasping and manipulation. The fingertip is robust, provides high spatial resolution (in average $\approx$5.5 mm) and is very sensitive to first touch. Parameters such as friction, fingertip softness and the force range of interest can easily be adjusted by replacing the sensor material and the pull-up resistors, respectively.

We now plan to integrate the manufactured sensor fingertips into our Shadow Robot Hands. However, we are continuing to test numerous sensor materials, in an endeavor to allow further miniaturization and possibly achieve even higher spatial resolutions. Finally, plans are in motion to integrate the developed fingertip sensor into hand prosthesis, which holds the possibility of restoring patients' sense of touch in their fingertips. To convey the tactile data to the user, we are considering non-invasive information transmission using visual channels, such as a graphical tactile overlay map of fingertip tactels on see-through video goggles (such as Google's Project Glass[4]).

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