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High-resolution tactile display operated by an integrated „Smart Hydrogel“ actuator array

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ABSTRACT

Here we introduce a high-resolution tactile display based on the integration of 4,320 actuators with a density of about 300 actuators per cm² into an array displaying both visual and tactile information. The actuators are fabricated simultaneously by UV-patterning. Intrinsically active polymers called "smart hydrogels" are used as actuators which are sensitive to changes in temperature. The high resolution temperature field is controlled by a computer using an optical interface that is controlled by a computer. Thus the temperature is adjusted for each actuator and it can be independently controlled. An actuator pixel changes color from transparent to opaque providing a visual monochrome functionality. The altitude and the elasticity change as well. Therefore the tactile display is able to generate artificial impressions about contours, textures, profiles and the softness of a surface. The actuators are covered by a thin foil equipped with knobs, which can additionally vary the tactile impressions. For fabrication an inexpensive modified dry photoresist technology was used for the masters of up to (200 x 155) mm². This device demonstrates a high integration into MEMS with a monolithically fabricated actuator array of temperature-sensitive active polymer and an optoelectronic control.

Keywords: high-resolution tactile display, large-scale integration technology, MEMS, hydrogel, PNIPAAm, intrinsically active polymer, actuator

1. INTRODUCTION

Within the last thirty years microelectronics changed our life and work significantly. Therefore it is certainly consequent to ask about the potential of microelectromechanical systems (MEMS) containing hundreds or thousands of components. A closer look at the technology reveals that the initial expectation that modified semiconductor fabrication technologies would be readily adapted to many other large-scale integration applications (LSI, 100 to 10 000 components) has only been fulfilled in very few cases such as the digital micromirror devices (DMD).^[1] For most other micro-actuator applications the semiconductor technology is too expensive and does not offer sufficient performance and the necessary functionalities. Polymeric MEMS fabricated with inexpensive technologies can offer a suitable solution.^[2] One large area, which can benefit from MEMS technology is that of the enhanced imaging systems for presentation of media with additional tactile impressions.

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Here we present a tactile display (Fig. 1) which points out a material-based approach to polymeric large-scale integrated MEMS using the stimuli-responsive polymer poly(*N*-isopropylacrylamide) (PNIPAAm) acting as the active functional unit, i.e., the actuator. This material can reversibly change its volume by swelling or shrinking more than 90% in response to small alterations in certain physical^[3] or chemical^[4] properties of its environment. A simple set-up allows simultaneous but individual control of a large number of random elements, which can be used to display shapes and structures.

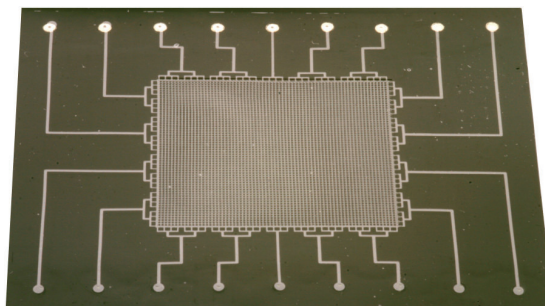


Figure 1. The high resolution tactile display consisting of 4,320 (60x72) actuator pixels at an element density of 297 actuators per cm²

2. DESIGN AND FABRICATION

2.1 Materials

The monomer *N*-isopropylacrylamide (NIPAAm), the crosslinking agent *N,N'*-methylenebis(acrylamide) (99 %) (BIS), the photoinitiator 2-hydroxy-4'-(2-hydroxyethoxy)-2-methylpropiophenone (98 %), and pure ethanol (99,9 %) were obtained from Aldrich. The adhesion promoter 3-(dimethylchlorosilyl)propyl methacrylate (DPMA) (85 %) was received from Fluka. Distilled water was used to prepare photopolymerizable solution. Poly(dimethylsiloxane) (PDMS) was received as RTV 615 A/B from Momentive Performance Materials. As black polyester substrate TypoPhot TO-G from Typon Graphic Systems AG is used.

2.2 Photo-patterning of hydrogel

The photo-patterning of the stimuli-responsive hydrogel was realized by photolithographic polymerization of PNIPAAm by UV exposure. The equipment consists of a Hg lamp HBO 100W/2 (Osram), a filter with low-pass characteristics (>200 nm), and an aperture to parallelize and bundle the UV light. The polymerisation chamber was rinsed with argon and filled with polymerizable aqueous solution consisting of 14.3 wt.-% NIPAAm, 2 wt.-% crosslinking agent BIS, and 2 wt.-% photoinitiator. UV exposure of 75 mW cm⁻² was performed through a photomask (TypoPhot TO-G, plotted by a Herkules Imagesetter with 5080 dots per inch) at 5 °C. Non-polymerized residues were removed by a rinsing step with ethanol and water. The quality of the hydrogel layer depends on the polymerization time, which depends on the pitch of the polymerization mask and on the thickness of the hydrogel layer.

Optimal results have been obtained with an exposure time between 60 s for a pitch of 200 µm and hydrogel thickness of 100 µm, 28 s for a pitch of 580 µm and a thickness of 300 µm, and 22 s for a pitch of 1000 µm and a thickness of 500 µm (Fig. 2a). A shorter exposure time affects both adhesion properties and pattern accuracy, while a slightly longer time does not have a strong influence on the exposure result.

The aspect ratio of the actuators is restricted to 2.5 times height to width by its mechanical stability. To obtain a covalent bonding of the gel actuators the cover foil was prepared with the adhesion promoter DPMA. The foil was treated 45 min with low pressure oxygen plasma (Plasma-Cleaner Harrick Sci. PDC-002) and dark stored for 48 h in an ethanol : DPMA mixture (99.5 : 0.5 volume ratio).

After rinsing with pure ethanol and drying with argon, the materials were processed immediately. On the polyester substrate the hydrogel adheres without any pre-treatment. The three layers can be seen in (Fig. 2b).

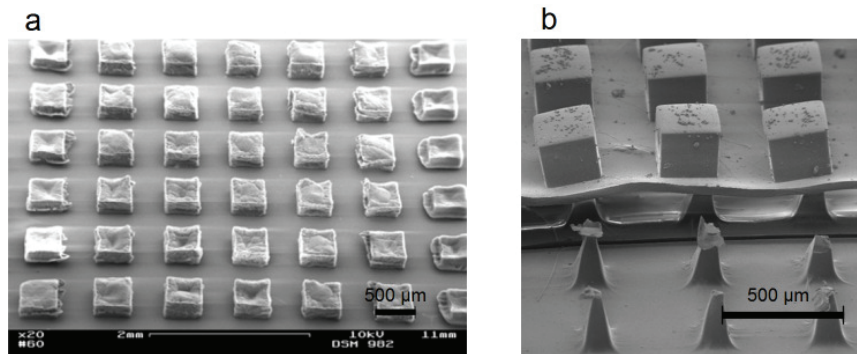


Figure 2. a) SEM image of Photolithographic UV-patterned hydrogel actuators on a polyester substrate. b) SEM image of the three layers – substrate, dried hydrogel actuator matrix and cover foil, which was cut and partly removed.

2.3 Fabrication of large-sized master moulds

The prototyping of the masters is based on a modified dry photoresist technology, which was originally used in the printed circuit board fabrication. This technology is inexpensive, rapid, does not need microfabrication facilities and allows the fabrication of large-sized masters up to (200 x 155) mm². After laminating the dry photopolymer Dynamask 5030 onto copper-coated standard board material FR 4 (0.2m min⁻¹ at 105 °C, Bungard RLM 419P) the photoresist has been exposed to UV light through a photomask, developed by KOH rinsing and finally dried.

2.4 Fabrication of the cover foil and of the device

The PDMS device is realized using the multilayer soft lithography.^[5] To fabricate the PDMS cover foil a mixture of base A and curing agent B at the ratio 3:1 was filled inside the knob master mould, degassed, covered by a glass substrate and polymerized (1.5 h at 80 °C). The body of the device, which contains the chamber of the active layer and the channels of the swelling agent supply, was also realized by PDMS replica molding (A to B ratio 30:1). On the bonding areas the polyester substrate was coated with a thin 3:1 PDMS mixture. Finally, the compounds of the device (cover foil, active layer and PDMS coated substrate) were bonded by 80 °C heating for 1.5 h and after that permanently compressed by a metal housing.

2.5 Optoelectrothermic control

For optoelectrothermic control a business video projector Christie Roadster S + 20K (digital light processing DLP, 3.000 W Xenon Bubble lamp, 20.000 ANSI lumens) is used. The device is equipped with optics consisting of a zoom lens 4.5-7.3:1 and a convex lens $f = 300$ mm. The active tempering of the bottom side of the substrate is done by water cooling tempered by a refrigerated circulator Julabo F33-EH. For experiments with a common video projection system an unmodified common EPSON EMP-820 is used, additionally equipped with an optics consisting of a convex lens $f_1 = 90$ mm and an objective with $f_2 = 80$ mm.

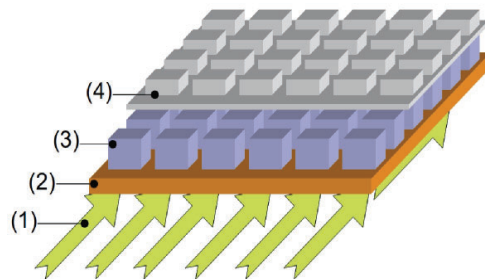


Figure 3. Setup consisting of (1) fluid tempering, (2) substrate, (3) hydrogel actuators, (4) cover foil with a knob on top of each actuator.

2.6 Design

The heart of the high resolution tactile display (Fig. 1) is a LSI actuator array, which consists of an active polymer layer of the stimuli-responsive hydrogel poly(*N*-isopropylacrylamide).^[6] This material can reversibly change its volume by more than 90 % swelling or shrinking in response to small alterations in certain physical^[3] or chemical^[4] properties of the ambient parameters. The simple setup (Fig. 3) consists of the photo-patterned active PNIPAAm layer (3), which is covalently bound to a PDMS cover foil with knobs (4) as well as fixed to a black polyester substrate (2). The pitch of the active array is 580 μm containing the actuators with a footprint of (300 x 300) μm^2 and a swollen height of 500 μm as well as a 280 μm space between the actuators. The spacing room is used as swelling agent supply for the actuators, storing and releasing water. The actuator array unit is connected with 18 channels providing an adjustable swelling agent control. In our tactile device 60 x 72 actuators are arranged in an array with a spatial actuator density of 297 elements per cm^2 .

2.7 Functional principle

Due to the volume phase transition behavior, PNIPAAm can be reversibly switched from the completely shrunken state to the swollen state by temperature alteration between 29 °C and 35 °C (Fig. 4a). This corresponds to a “switch on” or a “switch off” of a PNIPAAm actuator between the extreme states (fully swollen or shrunken) as illustrated in (Fig. 4b). The control mechanism simply has to perform a small temperature difference of 6 K. The base temperature is supplied by a fluid (1) cooling the bottom side of the substrate (Fig. 3).

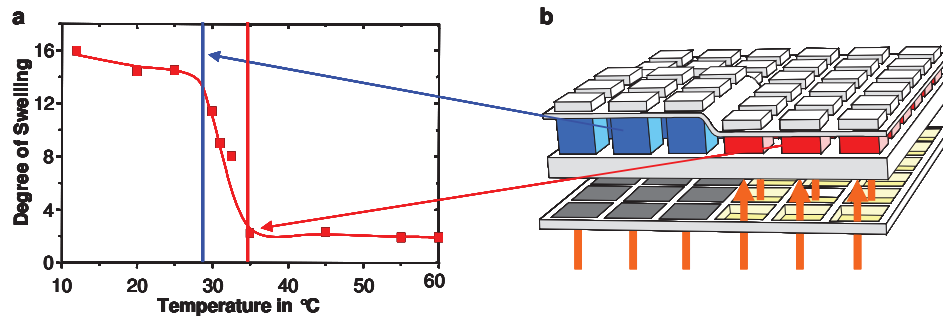


Figure 4. a) Swelling characteristics of the PNIPAAm hydrogel and requirements for the optoelectrothermic control.
b) Functional principle using an array of thermo-sensitive active hydrogel actuators to display a tactile 3D image.

A parallel control of each individual element of the actuator array is provided by optoelectronic control of a light-induced temperature field. A digital micromirror device controls the projection of a powerful light beam onto the substrate. By absorption the black substrate converts the light into heat and transmits it directly to the actuators attached on the surface.

3. BEHAVIOR OF THE DISPLAY

3.1 Time behavior of the optoelectrothermic control

The light-induced temperature field on the surface of the black substrate appears nearly in real-time. The temperature-field is completed after 400 ms (Fig. 5a-c). The temperature within the illuminated area is at least 35 °C while the temperature outside this area is does not exceed 29 °C. The active water cooling on the bottom side of the substrate dissipates the excess heat and keeps high resolution temperature field, which is displaying a dolphin shape, stable for the desired period of time (Fig. 5d).

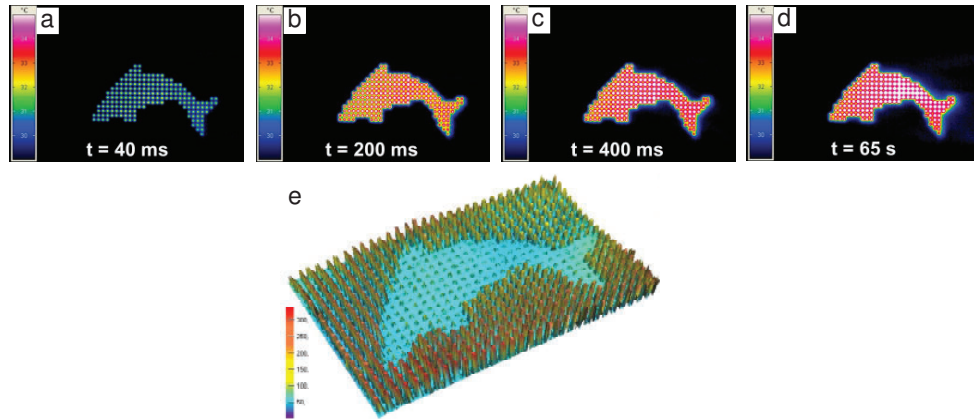


Figure 5. a-d) Thermography images of the temperature field applied to the hydrogel actuators which generates the image of a dolphin almost in realtime. e) Laser profilometry image of the hydrogel matrix which is displaying the outlines of a dolphin.

Furthermore, the active tempering provides independence from the ambient temperature. The actuators within the T -field are heated above the phase transition temperature and map the dolphin by shrinking (Fig. 5e).

While both the generation of the working temperature difference ΔT_{Work} and the cooling down of the temperature field occur nearly in real-time, the actuator response is more time-consuming.^[7] It can take several seconds. The response time of the swelling and shrinking processes can be lowered by increasing the working temperature ΔT_{Work} , corresponding to the highest and lowest temperature at which the actuator is operated, or by optimization of the actuators e.g. using an optimized hydrogel.^[8]

3.2 Actuator density

According to the features which have to be displayed with a higher resolution more detailed tactile pictures can be produced. The resolution is defined by the pitch x_p and depends on the actuator density D_A which is given by:

$$D_A = \frac{1}{x_p^2} \quad (1)$$

The pitch is determined by the functional requirements of the device and by the ability of the control to provide independent individual control of two neighboring actuators between their antagonistic extreme states “fully swollen” and “fully shrunken”. As shown in (Fig. 4), to perform the switching operations a difference of the working temperature $\Delta T = 6 \text{ K}$ has to be realized. This temperature difference requires a spacing x_{Res} between the two actuators, which represents the highest feasible resolution of the device. When the working temperature difference ΔT_{Work} of the optoelectrothermic control is bigger than 6 K, then a minimum size of the actuators has to be respected. In the asymmetric case the minimum size of the swollen ($2x_{A1}$) and shrunken ($2x_{A2}$) actuators are different and the pitch x_p of the actuator array is given by

$$x_p = x_{\text{Res}} + x_{A1} + x_{A2}. \quad (2)$$

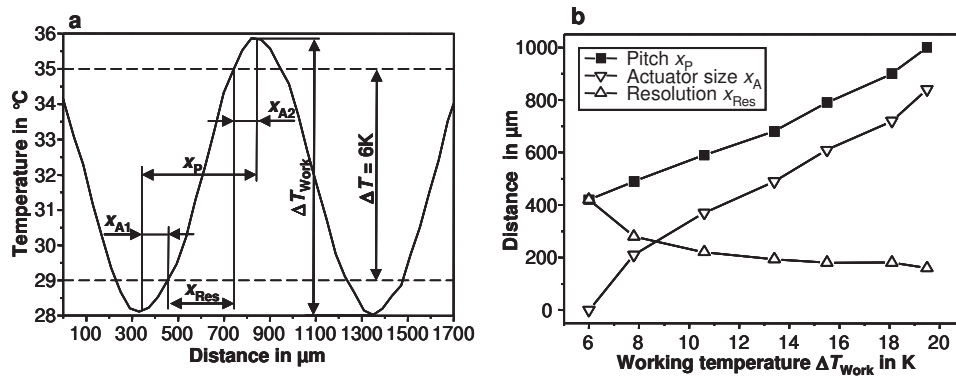


Figure 6. a) Characteristic temperature profile through the center of an actuator line. b) Relationship between the pitch x_p , the actuator size x_A and the resolution x_{Res}

The ΔT_{Work} is smaller than the highest possible temperature difference realizable with the optoelectrothermic control if the whole surface is heated without a pattern. The position of ΔT_{Work} is adjusted by the active water cooling on the bottom side of the substrate and by this the temperature profile displayed in (Fig. 6 a) is shifted to a higher or a lower temperature for a best possible actuator control between 29°C and 35°C.

At a working temperature difference of $\Delta T_{Work} = 6$ K the contribution x_A vanishes and the pitch x_p equals the resolution x_{Res} (Fig. 6b). At this working point the pitch has a minimum value of 420 μm providing an actuator density of 566 elements per cm². An increase of ΔT_{Work} improves the resolution but increases the smallest possible actuator size x_A and the pitch. Because of functional aspects, especially to provide mechanically stable actuators (determined by the aspect ratio of the actuator's height : size x_A) and the second functionality of the spacing between the actuators to store the swelling agent, we defined a pitch $x_p = 580$ μm consisting of $x_A = 300$ μm and $x_{Res} = 280$ μm. To provide these parameters the working temperature difference has to be between 7.8 K and 10.6 K.

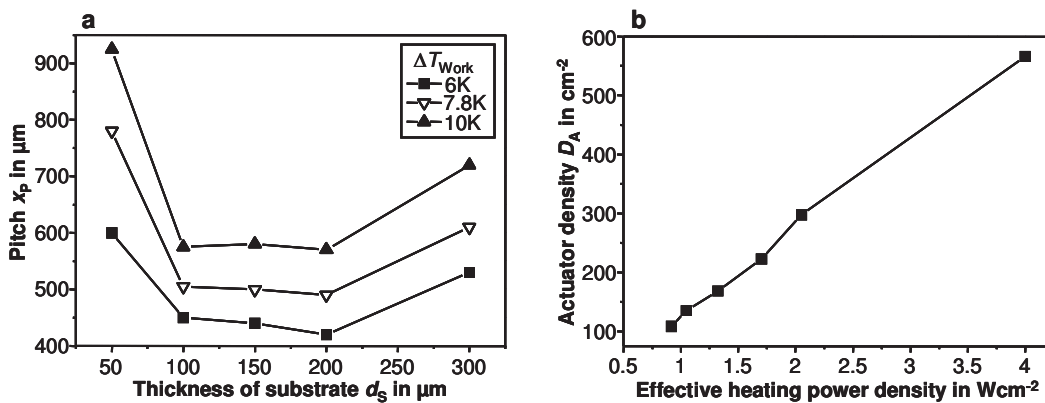


Figure 7. a) Pitch – substrate thickness correlation at a constant heating power in dependence upon the working temperature T_{Work} . b) Highest possible actuator density in dependence upon the heating power density

The highest possible spatial actuator density can be preset by the design parameters and the effective applied heating power. As design parameters for a high achievable actuator density, the material and thickness of the actuator array's substrate are of particular importance. The material should have a low specific heat conductivity and a good optical transmission at the used light wavelength. Transparent standard polymers, such as polymethacrylate, polyester, polystyrene and PDMS provide suitable heat conductivities in the range of (0.14 ... 0.22) Wm⁻¹K⁻¹. Here, we use polyester as substrate material with $\lambda_s = 0.2$ Wm⁻¹K⁻¹. One side of the substrate is black, thus the energy of the light is most effectively converted into heat. The thickness of the substrate d_s influences the performance of the optoelectrothermic control at a given heating power density. However, the lowest possible pitch can be obtained with a

substrate of the proper thickness, which in our case is 200 μm (Fig. 7a). Too thin and too thick substrates significantly decrease the maximum actuator density.

The heating power density determines the size of the controllable area and the actuator density. Figure 7b indicates that for the working point at $\Delta T_{\text{Work}} = 6 \text{ K}$ (on which $x_p = x_{\text{Res}}$), an increased heating power density a higher actuator density can be controlled. The Christie business video projection system used provides a heating power density on the actuator array substrate of about 4 Wcm^{-2} and an actuator density of 566 cm^{-2} at a pitch of $420 \mu\text{m}$, whereas the controllable size of the actuator array is $4 \times 5.5 \text{ cm}^2$ (22 cm^2). For some applications a common video projector will be sufficient. For example an EPSON EMP-820 device containing a 200 W lamp (2.500 lm) with additional optics is able to control an area of 2.66 cm^2 and provides an actuator density of about 100 cm^{-2} at a resolution of $960 \mu\text{m}$.

3.3 Display Functionalities

With this tactile display different types of information can be presented. Immediately after heating above the phase transition temperature of about 34°C the PNIPAAm actuators change their color from transparent to opaque within the dolphin-shaped temperature field and monochrome visual information is displayed (Fig. 8a). After completion of the shrinking process the contours of the dolphin are mapped with single pixel accuracy (Fig. 8b). The tactile information is based on changes in the height of the actuators (from $500 \mu\text{m}$ at swollen state to about $250 \mu\text{m}$ at shrunken state) and in their softness. A smooth surface of the cover foil displays preferably differences in softness. Transferable impressions reach from the softness of fatty tissue at the swollen PNIPAAm state (Young's modulus $Y = 13 \text{ kPa}$ at 21°C) to the wood-like surfaces displayed by shrunken gel ($Y(40^\circ\text{C}) = 100 \text{ kPa}$).

Because differences in height are hardly palpable on the soft hydrogel surface, the cover foil is equipped with knobs, which enhance the edges (Fig. 4b). The tactile information is determined by size, shape and sharpness of the knob edges. While sharp-edged, larger knobs are better qualified to show outlines, smaller, rounded knobs improve the diversity of displayable textures. A higher knob density seems to enable displaying both outline and softness information. An interesting option to "freeze" the surface's image is offered by evacuation of the actuator array's swelling agent.

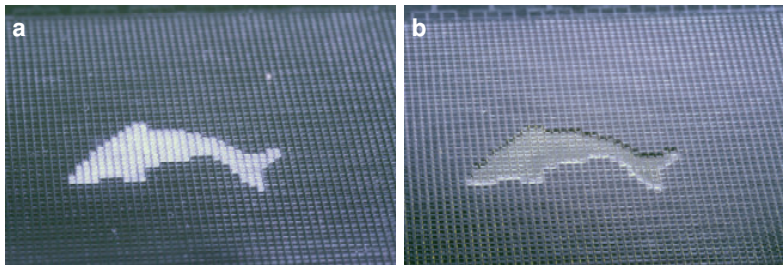


Figure 8. Functionalities of the display. (a) Visual monochrome function; (b) Tactile function displaying a palpable image.

4. CONCLUSIONS

Compared to other mechanical actuator arrays the hydrogel actuator matrix used here is an up- and downscalable, low complexity solution which can be manufactured monolithically by UV-light photo-patterning and by means of the lithography. With the optoelectrothermic control used, a high resolution temperature field could be generated which is able to independently control the temperature-sensitive smart-hydrogel actuators. Since with the optimized demonstrator parameters an actuator density of 300 actuators per cm^2 could be reached, this device is a high resolution tactile display demonstrating a high integration of MEMS. Furthermore, in microfluidics such integration could open new dimensions of fluidic processing.^[9]

Combining these devices with image-based diagnostics in the future could provide new features in teleoperations such as the tactile recognition of objects inside a body without the necessity to open it. This would improve diagnoses or even allow preliminary simulation of surgical operations. The minimally invasive robotic surgery (MIRS) which reduces the operative trauma for the patient could be enhanced by the possibility of the tactile recognition of the operation field which is an important advantage of the conventional open surgery.

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