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Multimodal, High-Resolution Imaging System Based On Stimuli-Responsive Polymers

Georgi Paschew[1,a], René Körbitz[1,b] and Andreas Richter[1,c]

[1] Technische Universität Dresden, Polymeric Microsystems, D-01062 Dresden, Germany

[a]georgi.paschew@tu-dresden.de, [b]rene.koerbitz@tu-dresden.de,

[c]andreas.richter7@tu-dresden.de

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Abstract. Providing realistic impressions about a virtual ambient for interaction with human's auditory, visual, and tactile perception is one of the core challenges of modern imaging systems. However, particularly tactile displays with high spatial resolution implemented as a large-scale integrated microelectromechanical system are not yet realized. Here, we report on a multimodal display with thousands of actuator pixels, which generates both visual and tactile impressions of a virtual surface. The fully polymeric, monolithically integrated device consists of an actuator array made from poly(N-isopropylacrylamide). This material is a stimuli-responsive, particularly temperature-sensitive hydrogel. Controlling the actuator temperature via an optoelectrothermic interface between an upper and lower temperature the actuator can be switched from the swollen to the shrunken state (volume change up to 90%) in several hundred milliseconds. To benefit from this highly dynamic behaviour it is necessary to use a control unit which provides the required temperature changes also in the range of milliseconds. For characterizing the time behaviour of our optoelectrothermic control unit we use the change in transparency of PNIPAAm caused by the phase transition. In this paper we preferably discuss the time behaviour of the display devices.

Introduction

Humans have five senses to collect a huge amount of information about their environment. In fact, only two of them, the auditory and the visual perception, are used by common technical devices as communication channel. Especially the sense of touch offers a great potential of revolutionizing the interaction between people, modern media and mobile devices. To complement other sensory channels by tactile perception, it is necessary to manage some core challenges: the system has to provide a high spatial resolution, a defined change in height and a specified actuator force. To meet several of these requests, in most common tactile devices electro-mechanic actuators are used to generate haptic impressions [1]. We strike a new path and use a microelectromechanical system (MEMS) to implement the desired tactile functionality. The full polymeric, monolithically integrated device consists of an actuator array made from poly(N-isopropylacrylamide) (PNIPAAm). This material is a stimuli-responsive, particularly temperature-sensitive hydrogel which reacts to small alterations in certain physical [2] or chemical [3] properties. In fact, increasing the temperature from 29°C to above 35 °C causes a shrinking of the gel up to 90 % (Fig. 1) and a color change from transparent to opaque. These effects are fully reversible and can be used to create 3D-profiles and monochrome images which means that it will be possible to use two communication channels with one device. That opens up the possibility to assign functions and types of information to the channel which is best suited for their presentation.

Photo-patterning of hydrogel

Photopolymerization. For the polymerization of PNIPAAm an aqueous solution consisting of 14.3 wt.-% NIPAAm, 2.0 wt.-% crosslinking agent N,N'-methylenebis(acrylamide) (BIS) and 2.0 wt.-% photoinitiator (2-hydroxy-4'-(2-hydroxyethoxy)-2-methylpropiophenone) was prepared. The photopolymerization of PNIPAAm was carried out under UV irradiation (75 mw/cm², 28 s) generated by a mercury lamp (HBO 100W/2, Osram). The UV light was bundled and parallelized by an aperture. To remove oxygen, the polymerization chamber was rinsed with argon and filled with the aqueous solution. A photomask was used for photo-patterning of hydrogel actuator cubes.

Functional principle

Setup of thermal control. The thermal control system has two important tasks: 1) to generate a high resolution thermal field 2) to dissipate excessive heat for a steady-state stable thermal image. Using a combination of a focused heating on top of the substrate and at the same time an active cooling water circulation both requirements can be met. A light beam with a high energy density is used for the purpose of heating. On top of the substrate a thin black layer converts the light into heat. All other substrate layers and the liquid coolant have to be transparent. The hydrogel layer is covalently fixed on top of the substrate and covered by a foil (Fig. 1).

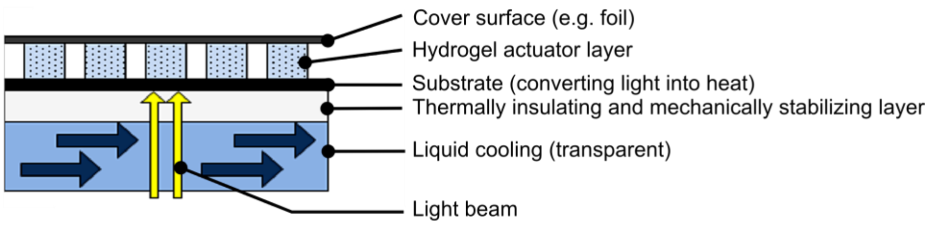

Fig. 1. Scheme of thermal control setup.

Hydrogel functionality. For controlling the optical properties and the volume of the actuators we use the phase transition of PNIPAAm which is a hydrogel with a lower critical solution temperature. It is possible to reversibly switch them from a swollen and transparent state to a shrunken and opaque state by a temperature variation between 29 °C and 35 °C (Fig. 2).

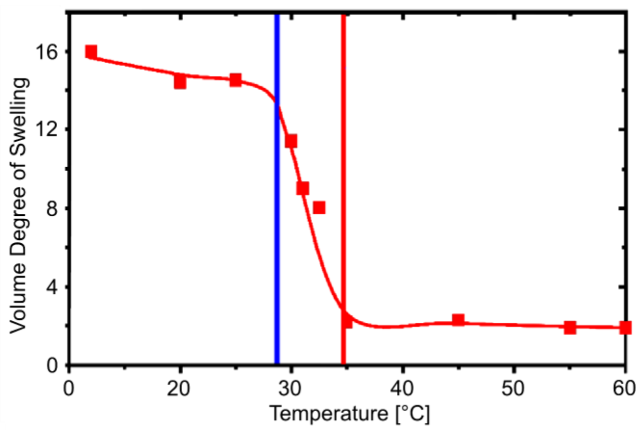

Fig. 2. Illustration of volume phase transition of the "smart hydrogel" PNIPAAm actuator.

For proper hydrogel actuation the control unit has to provide a small temperature difference of 6 K. To achieve a high resolution for the tactile display it is further necessary to control a large number of individual actuators at the same time without mutual interference. These requirements can be met by our optoelectrothermic control. The powerful light beam of a business video projector Christie Roadster S + 20K (digital light processing DLP, 3000 W) is focused on the black substrate where the absorbed light is most effectively converted into heat (Fig. 3).

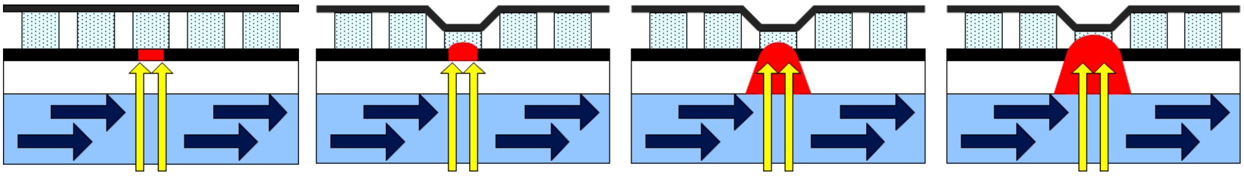

Fig. 3. Functional priciple of thermal control. 1) start of heating, 2) actuation, 3) heat spreading, 4) steady state

Time behaviour

Thermal control unit. Due to a thermal optimization, the light-induced temperature field occurs nearly in real time, more precisely after 400 ms, on the surface of the black substrate. To prevent lateral heat dissipation and to keep the temperature constant for a desired period of time, an active water cooling is applied on the bottom side of the substrate. Further the base temperature of the water cooling defines the working point and can be described as a global offset to the thermal image.

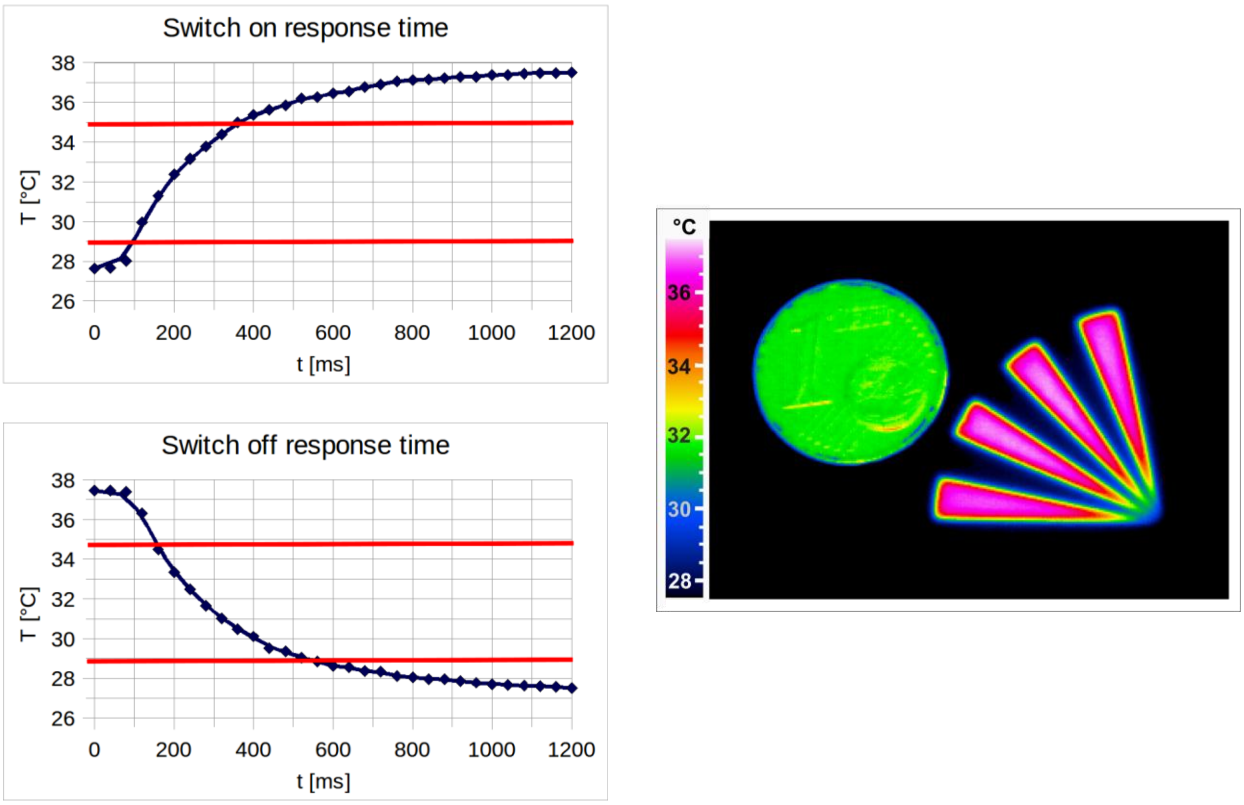

Fig. 4. Response time of the thermal control unit and high resolution temperature image.

In figure 4 a change of 6 K between 29°C and 35°C can be observed within 400 ms. During the heating process the temperature alternation occurs between 100 ms and 350 ms. The lower chart shows the cooling down process of 370 ms which is slightly slower.

Time behaviour with 520 µm hydrogel layer. The characterization with infrared-imaging was observed on the pure black substrate which converts the light energy directly into heat. The air on top of this layer exhibits a low thermal capacity and resistance, leading to a better dynamic behavior than in the relevant case of application. In case of a hydrogel layer and water on top of the heat-converting layer we have to take into consideration the higher thermal capacity. Consequently, more time is needed to achieve the desired temperature change of 6K. For characterization of the setup we use a 520 µm thick layer of PNIPAAm. The colour change of the hydrogel from transparent to opaque during the phase transition is monitored with an optical video-analysis-system. Figure 5 shows the opaque image of the hydrogel layer at the different points in time.

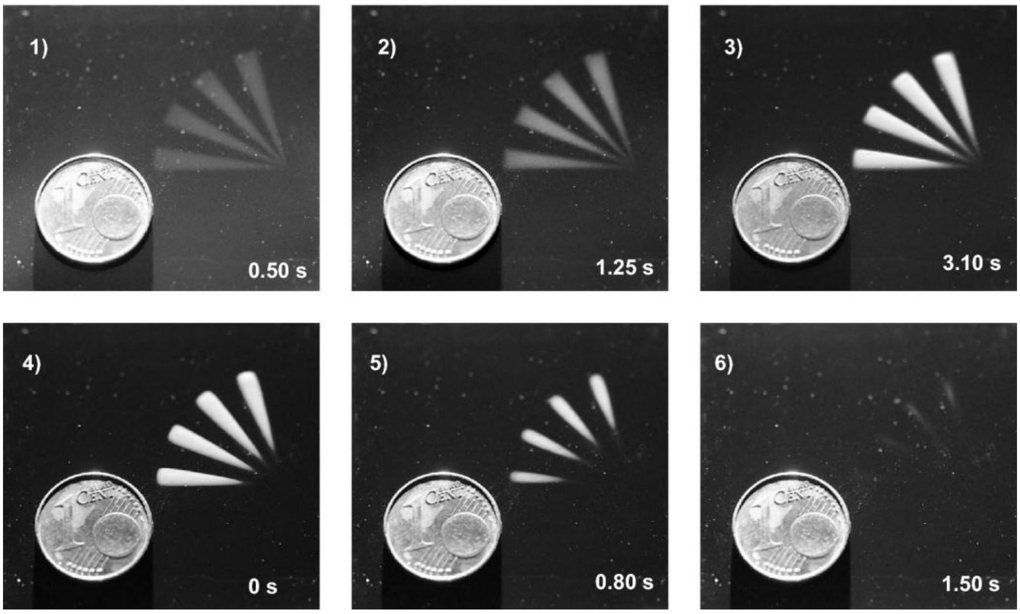

Fig. 5. Generation of a monochrome image due to an applied temperature change.

The steady-state time for both the light switching of the projection system and the reaction time of the video-analysis-system is about 90 ms which can be considered as measurement uncertainty. The first indication of an opaque colour due to a hydrogel phase separation can be observed about 500 ms after the light appears on the heat converting substrate (fig. 5.1). After 3.1 s the steady state is reached. The disappearing of the opaque areas can be observed in (fig. 5.4) to (fig 5.6) after switching off. It takes about 1.5 s until the image disappears. As previously assumed generation and disappearance of the temperature field within the hydrogel layer needs more time. In fact, the 520 µm PNIPAAm-water layer increases the reaction time of thermal control by a factor eight.

3D-Function

Display functionality. This display allows the presentation of different types of information. As mentioned the phase transition and the change from transparent to opaque can be used for displaying of monochrome images with a high resolution. A new type of high resolution tactile impressions is generated due to the change in the height of the actuators (from 500 µm in swollen state to 250 µm in the shrunken state). Furthermore tactile impressions are also enhanced due to the change of softness of the hydrogel layer which reaches from the softness of fatty tissue at the swollen hydrogel state (Young's modulus Y = 13 kPa at 21 °C) to the wood like surfaces displayed by shrunken gel (Y(40 °C) = 100 kPa) [4,5]. Additionally a special cover foil with knobs is used to improve the tactile detection of the outlines (fig. 7).

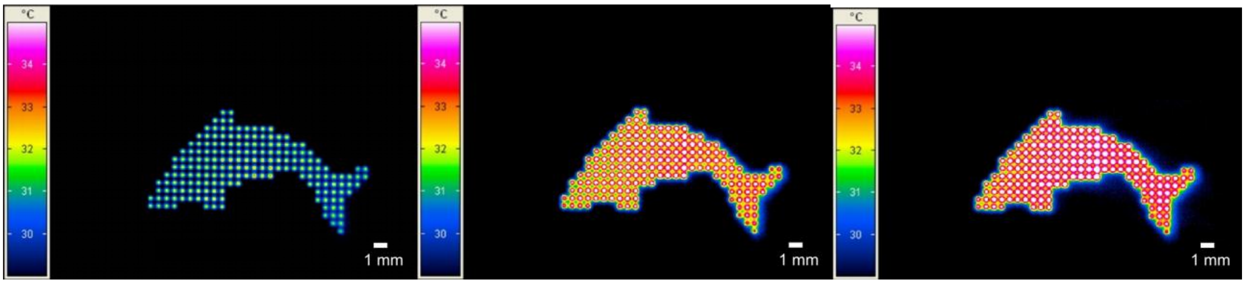

Fig 6. Thermal control of a dolphin shaped image. 1) 40 ms, 2) 200 ms, 3) 400 ms

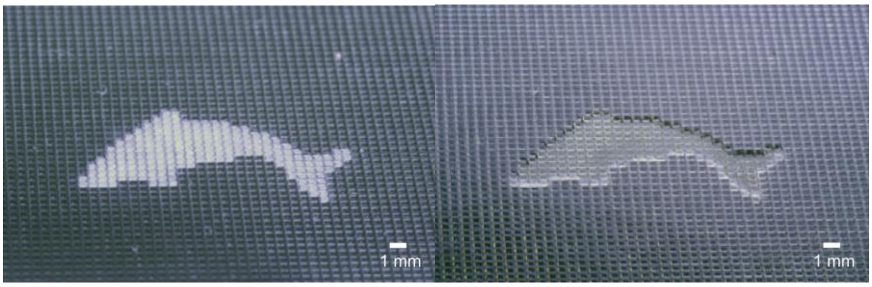

Fig. 7. Monochrome and tactile display output.
1) phase separation of hydrogel and opaque colouring, 2) resulting contours/outlines after actuation

Our tactile display consists of a matrix like arrangement of 65 x 65 hydrogel actuators with a pitch of 580 µm and a footprint of 300 µm x 300 µm. The system has an actuator density of 297 actuator per cm² and fulfills the requirements for a high resolution tactile display.

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