# IPMC Kirigami: a Distributed Actuation Concept

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***Abstract*—Today's mechatronics relies on conventional transducers, i.e. lumped sensors and actuators with rigid construction. Future consumer products, medical devices and manufacturing processes require sensing and actuation systems with high count and density of individual transducer units. Such systems can be addressed as distributed transducers. Building distributed sensing and actuation systems with conventional transducers is economically unaffordable, and an alternative solution is needed. In this work we propose and study a methodology to build such distributed sensor and actuator systems from soft bending smart material transducers. Individual transducer units can be separated from the planar material substrate by cutting and etching techniques, and transducer counts and densities are only limited by the available smart materials and equipment. In this study we use laser ablation techniques to separate individual transducer units from the ionic polymer-metal composite (IPMC) sheets, and produce translational actuation units on the bending material substrate. IPMCs are manufactured in-house, different bending structure geometries are studied, and four different designs of the cm-scale translational platform units are realized and validated experimentally. The results demonstrate that it is possible to etch and cut a multitude of actuation units into planar bending smart material transducers, that bending actuation can be used to realize translation, and that the designs can be further miniaturized. Therefore, bending smart materials can be utilized to build monolithic distributed transducers.**

***Keywords*—Kirigami, IPMC, Distributed, Actuation, Sensing.**

## I. INTRODUCTION

Today's field of mechatronics is limited by the properties of available transducers, i.e. the available sensors and actuators that activate the systems. These cannot meet the future requirements for increasingly affordable and simple designs, mechanical compliance, scalable dimensions, spatially distributed actuation and sensing, and high transducer densities. This demand for novel sensing and actuation capabilities is driving developments of smart material transducers, i.e. material level sensors and actuators [1]. Most interesting for mechatronic applications are the electromechanical and mechanoelectrical smart material transducers, such as dielectric elastomers [2], piezoceramics [3], piezopolymers [4], and other electroactive polymers [5]. These materials perform significant energy conversion between mechanical and electrical domains, and they can be directly coupled to electronics without the need for additional energy conversion stages, e.g. pumps in pneumatic actuators [6], heating wires in shape memory polymers [7], etc. While many studies have seen them as replacements of conventional transducers, they enable building qualitatively different sensing and actuation solutions that cannot be realized using conventional transducers, e.g. in MEMS [8], soft robotics [9], drug delivery [10], etc. These materials are also a potential solution for realization of simple and economically feasible sensing and actuation systems with high transducer counts and densities, further addressed as distributed transducers. Such systems are required in a variety of applications, including manufacturing processes in industry [11], human-machine interactions [12], [13] and novel consumer products [13], infeasible to implement with conventional transducers.

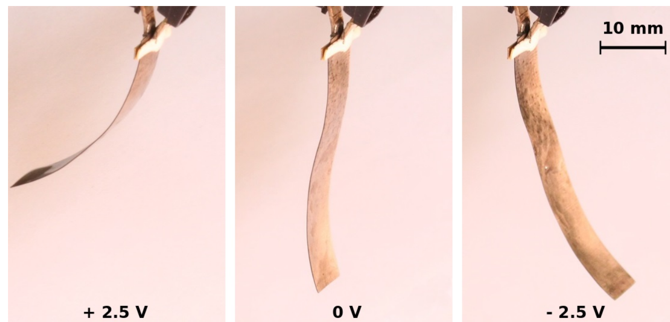


Fig. 1. IPMC actuation: the material at rest (center), and with 2.5 V applied at opposite polarities (left and right).

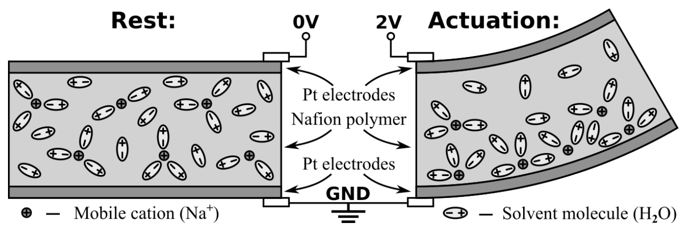


Fig. 2. Simplified explanation of IPMC construction and actuation principles. Ion-conductive polymer (thickness 180 $\mu$m in this study) is coated with (10$\mu$m thick) conductive electrodes. Loosely coupled ions migrate in electric field, dragging along solvent. This causes unevenly distributed hydrostatic and Coulomb forces, resulting in bending.

Constructing simple and affordable distributed sensing and actuation systems from soft smart materials requires development of methodologies that involve the least effort in design and implementation. Since most of the smart materials are simplest to manufacture in planar form, techniques are required to turn these planar materials into desired transducer systems. For this purpose we propose to use cutting, etching and deformation techniques inspired by kirigami, i.e. the art of cutting and folding paper. Previously similar concepts have

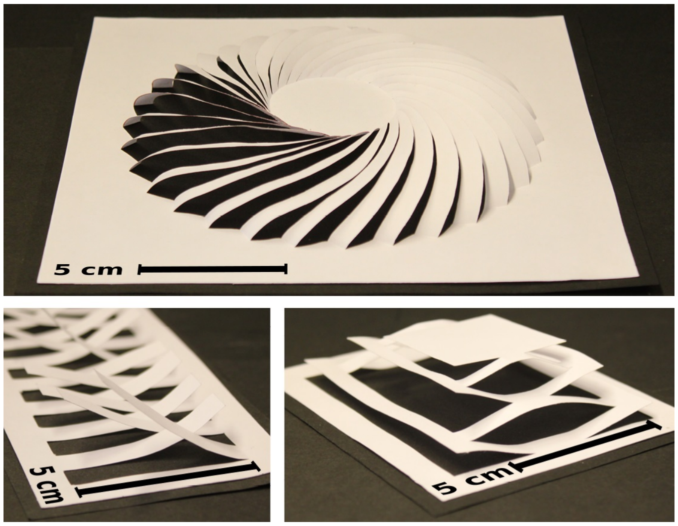


Fig. 3. The art of kirigami. Various 3-dimensional structures can be obtained by cutting, folding and curving a planar sheet of paper.

been used e.g. on passive materials to obtain 3D conductor structures [14], on active materials for assembly [15], or actuation purposes [16], [17]. In terms of electroactive materials, several authors have reported actuating micromirrors using piezoceramics, e.g. PZT [18] and aluminium nitride [19]. Also preliminary efforts have been made in cutting of the soft IPMC materials to obtain pumps [17], and several authors have studied etching of the IPMC samples to separate sensing and actuation regions [20], [21].

In this paper we report first efforts towards high strain monolithic actuator and sensor structures with a greater level of complexity from planar bending smart materials. We investigate the realization of structures that transform the bending of the soft smart materials into translational motion normal to material surface. First we manufacture the ionic polymer-metal composite (IPMC) samples by plating Nafion polymer with Pt electrodes (see Fig. 1 and 2). Next, we empirically study the influence of the beam geometry on the actuation capabilities. Further, we design four functional actuation units with different geometries, similar to the kirigami platforms shown in Fig. 3. These designs are implemented by applying laser ablation techniques on the IPMC materials. Behaviour of the resulting structures is studied, and lastly one of these designs is miniaturized by implementing four instances of it on a single IPMC substrate.

## II. Materials and methods

### A. IPMC properties and manufacturing

Ionic polymer metal composite (IPMC) materials are electroactive polymer transducers that are produced by coating ionic polymers with metal electrodes. They exhibit both sensing and actuation capabilities, i.e. they generate voltage in response to bending, and bend in response to voltage applied between their electrodes (see Fig. 1 and 2). These materials produce large strains (e.g. out-of-plane displacement of roughly 50% of beam length in Fig. 1) at low activation voltages (typically below 5 V) [22], [23], [24], and they are scalable and inherently compliant (Young's roughly between 100 MPa and 1 GPa [25]). Actuation bandwidth typically remains between 0.1 Hz and 10 Hz (limited by ion migration and beam inertia), but observable deflections from DC up to 100 Hz have been reported [25], [26]. While the application-maturity of these materials is limited by their performance [25], they well suit for demonstrating the distributed transducers' concept, and are constantly being improved.

IPMC transducers that are used in this study are manufactured in-house, similarly to the steps reported in [27], [28]. Commercial Nafion$^{TM}$117 membrane (Alfa Aesar) with 0.180 mm thickness is surface-roughened using a fine grit size sandpaper (ISO P1000), cleaned in ultrasonic bath, and coated with Pt electrodes by chemical reduction of Pt salt. The latter process involves infusion of metal particles into the material, and growing of the surface electrode thickness. For metal particle infusion the membrane is soaked in $[Pt(NH_3)_4]Cl_2$ complex (Sigma Aldrich) solution ($\geq$ 10 h), and further the platinum complex ions are reduced into metal nanoparticles by adding $NaBH_4$ (Sigma Aldrich) while heating the mixture to 60 °C. Electrodes are grown in thickness by placing the membrane into aqueous $[Pt(NH_3)_4]Cl_2$ and $NH_4OH$ solution, and slowly heating the solution to 60 °C, while incrementally adding $H_2NOH{\cdot}HCl$ and $NH_2NH_2{\cdot}H2O$ over the 4 hours period. Finally, the material is protonated in 0.1 M HCl solution, and ion-exchanged in 0.1 M NaOH solution, resulting in $Na^+$ counter-ion form.

### B. Material processing

In order to utilize IPMCs for implementation of distributed transducers it is necessary to establish suitable parameters for cutting the materials by laser ablation methods. For etching and cutting IPMCs we use the laser micro-machining system Optec WS-STARTER with theoretical laser focus spot of 7 $\mu$m. Suitable parameters for material processing (pulse energy, pulsation rate and cutting speed) are established experimentally, by applying test patterns (concentric circles with 0.3 mm to 1.5 mm diameter, 0.3 mm increments) to IPMC samples at different settings. The resulting cuts are validated and evaluated using optical microscopy (Keyence VHX-6000) and scanning electron microscopy (SEM) images (Jeol JSM-6010LA).

### C. Effects of geometry

The achievable range of IPMC deformations significantly depends on the resistance of their surface electrodes [29]. Therefore it is necessary to assure that the respective effects do not significantly impact the performance of the kirigami-inspired IPMC structures. For this purpose we experimentally study the influence of the material beam geometry on actuation capabilities. We use the Optec pulsed laser to realize four different actuator beam geometries that have similar dimensions to the structures later implemented in the actuation units. All of the investigated actuators are 3 mm long, and each of the four geometries is realized in four different widths: 0.5 mm, 1 mm, 2 mm and 3 mm, as shown in Fig. 4. All of these actuators are implemented on a single IPMC substrate in order to minimize performance variations that stem from clamping effects and variations in material properties. Characterization of actuation capabilities is performed through measurement of maximal tip deflections in response to 0.1 Hz bipolar rectangular wave input voltage with 2 V amplitude. Respective experimental set-up is described in section II-E (Fig. 6).

### D. Kirigami-inspired actuation units

This study of distributed transducers focusses on the concept of actuation unit elements that convert the bending motion of the smart material transducers into linear displacements normal to their surface. The investigated structures are inspired by the distributed and platform-like kirigami structures that can be produced by cutting and deforming paper, such as those shown in Fig. 3. In the following we explain the designs of these actuation units, the rationale behind them, and how we investigate their functionality.

The investigated four actuation unit designs are shown in Fig. 5, and they utilize either two (A and B) or four (C and D) actuation arms. Actuation units are mechanically clamped and electrically excited at their four sides, and the central ”platform” area rises or lowers out of the material plane during actuation. The designs with the same count of actuation arms differ by the number of sequential actuation units (each is rotated by 90° with respect to the previous one). While IPMC geometry is later shown not to significantly affect the actuation capabilities within the investigated range of IPMC dimensions (sections II-C and III), the actuator arms are designed such that they decrease in width along their length (Fig. 5). We expect this to decrease the voltage drop along multiple sequential actuator portions. The last narrow IPMC portions just before the mobile platform are meant to act as a torsional hinges. They also limit current propagation to the platform areas, therefore allowing to achieve functional designs with less efforts, i.e. without the need to etch away portions of IPMC electrodes.

Inspired by kirigami, the investigated actuation units consist of actuator elements, hinges and undeformed passive elements (both mobile and stationary). However, these actuation units significantly differ from paper kirigami since folding of smart materials is not permitted (i.e. difficult to implement), and all actuation functionalities are required to result from bending. Furthermore, for the sake of simple realization, the designs are required to achieve the desired functionality without changing the bending direction (i.e. mountain $\leftrightarrow$ valley), because this would require reversing the polarity of voltage within the structure (difficult to implement). In order to prevent constraints to motions, the structures need to allow longitudinal displacements that occur in the actuation elements while they bend. The designs must be realizable through separation of active and passive substructures using laser ablation techniques, by cutting or etching away regions of planar material sheets.


Fig. 4. IPMC sheet after laser cutting. The separated monolithic IPMC sample consists of clamping region (middle portion) and actuation units (top and bottom rows). The clamped sample is shown in Fig. 10.

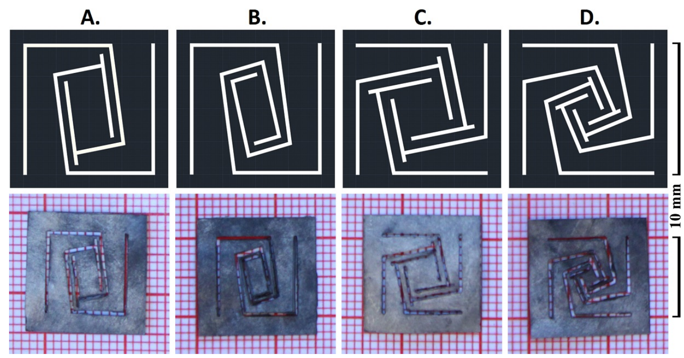


Fig. 5. Designs (top) and realizations (bottom) of the actuation units. We study raising IPMC platform designs with two and four actuator arms with different actuator net lengths.

The output regions in the actuation units (i.e. the mobile ”platforms”) should remain parallel to the material surface.

In order to validate the functionality of the designed actuation units we characterize their response to several sinusoidal voltage inputs using the second experimental set-up described in section II-E. Further we scale down one of these designs by factor of 4 (surface area), and report its behaviour as the first miniaturization effort.

### E. Experimental set-ups

We use two experimental set-ups for validating the steps of our distributed actuator design. The first one serves to characterize the quasi-static deformations of IPMC beams with different geometries. The second set-up is used for measuring the displacements of the designed IPMC transducer units in response to sinusoidal voltage inputs.

In order to measure the bending range of IPMCs with different geometries, the samples are clamped, bipolar rectangle wave voltages are applied, and material deformations are recorded using a camera. Arrangement of the experimental set-up is shown in Fig. 6. IPMC samples with different geometries and dimensions are manufactured on a single substrate (see Fig. 4) in order to reduce challenges in handling and clamping (i.e. electrical contact). The samples are clamped such that their clamping lines (contact edges between the material and the clamp) are vertical, circumventing gravitational effects. The materials are submerged in water during the experiments since they use water as solvent. We use Agilent 33220A function generator and a custom-built buffer amplifier (based

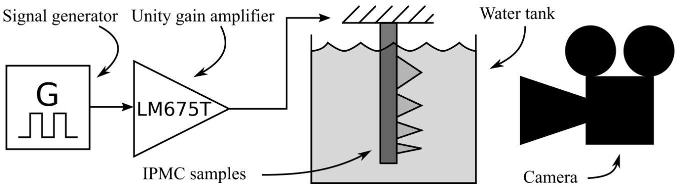


Fig. 6. Experimental set-up for measuring the quasi-static deflections of IPMC samples with different geometries.

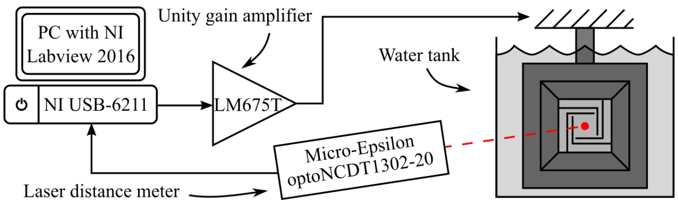


Fig. 7. Experimental set-up for measuring out-of-plane displacements of the investigated actuation units.

on LM675T operational amplifier) to apply bipolar square wave voltage with 10 s period and amplitude of 2 V. Motion of the IPMC samples is recorded using Canon T1i camera, and peak-to-peak deflections are afterwards measured from the video using the millimeter grid for reference.

The second experimental set-up, shown in Fig. 7, is used for validating the out-of-plane displacements of the investigated transducer unit designs. Actuation units (Fig. 5) are fixed and electrically connected by clamping them by the edges. Mobile portions of the actuation units can move in both directions normal to the IPMC surface. During the experiments the IPMCs are submerged in water such that the material plane is vertical, minimizing the effects of gravity. Actuation voltages are generated using a PC computer with NI Labview 2016 environment, and further applied to the IPMC samples via NI USB-6211 data acquisition board and a custom-built buffer (LM675 operational amplifier). Resulting displacements are simultaneously measured using a Micro-Epsilon laser triangulation sensor optoNCDT1302-20 via the same NI USB-6211 data acquisition board, in the same software.

## III. Results and discussion

This section presents the results of our first efforts towards the simple, affordable and miniaturizable distributed transducers with soft smart materials. In the following we describe and explain the results and observations of our experimental work.

Four large IPMC samples (roughly 50 mm by 75 mm each) were manufactured following the process described in section II-A. The resulting materials were observed to exhibit large displacements in response to low-voltage stimuli, i.e. $\leq 4$ V. One of the manufactured samples is shown in Fig. 8.

Laser ablation tests (see section II-B) on these IPMCs showed best results when executing 20 repetitions of the cut pattern at maximum laser power (15 W) and 20 mm$\cdot$s$^{-1}$ cutting speed. Microscopy image of the test patterns implemented on the IPMC samples are shown in Fig. 8. While lower laser wattages provided very fine cut tracks on the Pt electrodes,

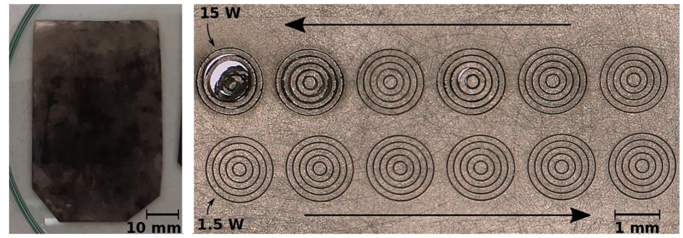


Fig. 8. A raw IPMC sample (left) that is manufactured according to section II-A, and a piece of this sample after the laser ablation parameter sweep (right). Horizontal arrows show the direction of increasing laser power. Diameters of the circles are 0.3 mm (inner) up to 1.5 mm (outer).

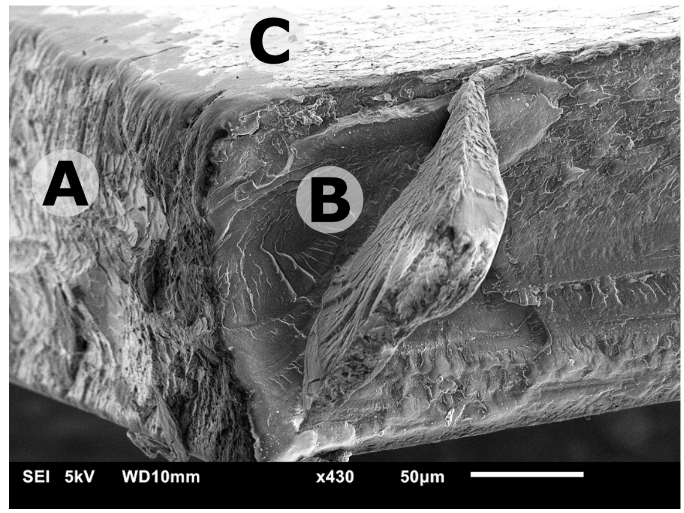


Fig. 9. SEM image of the laser-cut surface and its cross-section. Surface A is cut by laser, surface B resulted from breaking the IPMC sample after cooling it in liquid nitrogen, and surface C is the top electrode layer.

they could not penetrate the Nafion$^{\text{TM}}$117 polymer membrane, since the transparent polymer significantly dissipates the laser beam, instead of absorption. Quality of a penetrating cut is shown in an SEM image in Fig. 9, displaying the cross section of the cut and the adjacent surfaces. This sample was prepared by laser-cutting a straight line across the IPMC, cooling the sample in liquid nitrogen, and breaking it perpendicularly to the cut surface. While the cut surface appears clean, the high laser power results in roughly 50 $\mu$m wide cut track. Finer ($\leq$ 1 mm wide) IPMC structures were often damaged by excessive heating, and we occasionally observed residues of both electrode and polymer material left behind on the cut interface. Therefore, improved IPMC cutting techniques need to be established in our future work on miniaturization of the distributed transducers.

Realization of the monolithic IPMC sample that carries four different IPMC actuator geometries (with each geometry implemented in four different aspect ratios) was performed according to section II-C, and is shown in Fig. 4. These IPMC actuation units were then clamped as shown in Fig. 10, and actuation ranges of the individual actuators were measured using the first experimental set-up described in section II-E (Fig. 6). The ranges of deflection for all IPMC samples

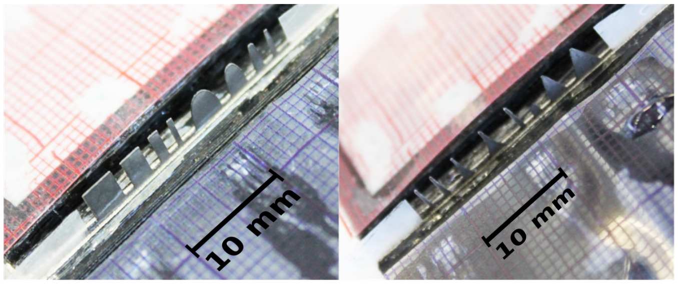


Fig. 10. IPMC actuators with different geometries are clamped for measuring their quasi-static displacements. Millimeter grid is fixed to the clamp, in the same plane with the tips of the IPMC beams. This allows to accurately focus the camera and later obtain position from the video.

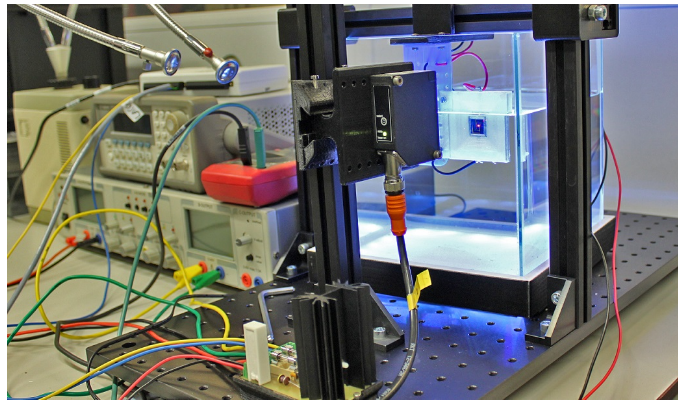

Fig. 11. Experimental set-up for measuring actuation unit deflections. IPMC is fixed in an aperture and submerged in water during experiments.

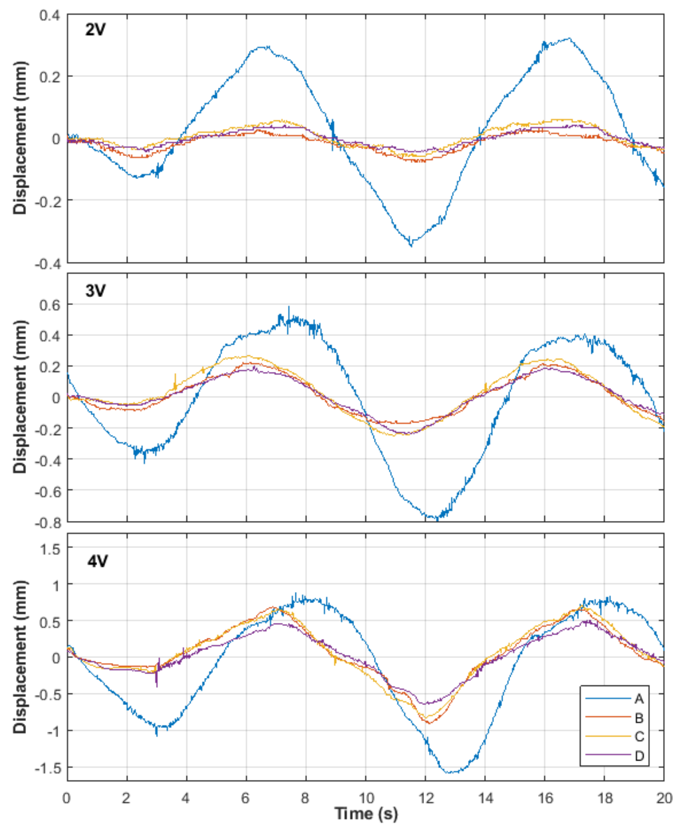


Fig. 12. Response of actuation units A, B, C and D (see Fig. 5) to 0.1 Hz sinusoidal voltage inputs with 2 V (top), 3 V (middle) and 4 V (bottom) amplitudes.

were very close (0.56 mm mean displacement), and varied only within the range that corresponds to 2 pixels in video resolution (0.07 mm). Thus, contrarily to our expectations, the IPMC surface resistance effects do not significantly influence the material performance within the range of investigated IPMC dimensions and measurement precision. Therefore, our distributed actuator unit elements are not constrained to any particular geometries at this stage; however more precise measurements are required (e.g. with laser-based measurement system) to identify the exact influence of the surface resistance effects, and the respective limitations to the geometries and loaded actuation.

The distributed actuator unit elements were designed according to section II-D, and the designs along with respective realizations are shown in Fig. 5. Actuation behaviour of all four actuation units was experimentally measured using the second experimental set-up described in section II-E (Fig. 7) and shown in Fig. 11. Displacements in response to sinusoidal 0.1 Hz actuation inputs with 2 V, 3 V and 4 V amplitudes are shown in Fig. 12. It can be seen that the implemented actuation units show large deformations, i.e. above 1 mm peak-to-peak amplitude at 4 V. While actuation units B, C and D exhibit similar displacement ranges, the unit A shows roughly 2 times larger deformations. We hypothesize that this is caused by local variations in the raw IPMC sample properties, and by laser ablation residues that appeared to some extent on all actuation units. Polymer remnants may locally constrain the motion, and miniature patches of electrodes may cause current drain on the cut edges, resulting in decreased actuation.

Finally, design "C" (Fig. 5) was miniaturized by placing four of these actuation units in the same 10 mm by 10 mm IPMC surface area, and the actuation functionality was experimentally validated. The resulting IPMC sample after manufacturing and during actuation is shown in Fig. 13. The difficulties in miniaturization were primarily related to laser ablation. Similarly to the effects described above, we observed heat damage to small structures, and some residues of polymer and electrodes that remained behind after the cutting. Therefore, the unit elements were proved functional, but improved cutting techniques are required for further miniaturization.

While implementation proved challenging, this preliminary study demonstrates that distributed actuation with bending smart material transducers is feasible. In future work we will continue investigating distributed transducer solutions for various functional designs, including tilting and rotating structures. In terms of implementation, we will improve IPMC processing techniques, optimize the actuation structures and explore utilization of other compliant bending smart materials, e.g. piezopolymers and dielectric elastomers.

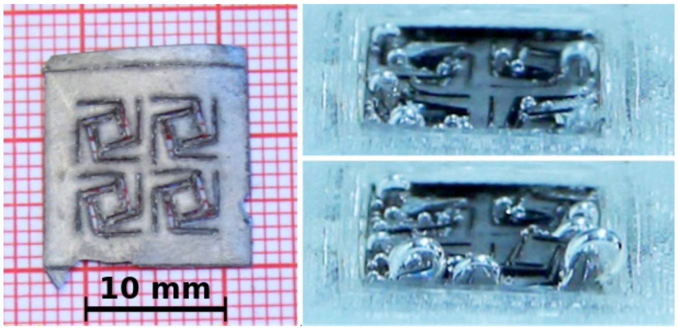


Fig. 13. Miniaturized actuation units. IPMC sample after laser cutting (left), and during actuation at 4 V input at opposite polarities (top and bottom on the right, images taken at 45° angle). Bubbles form due to electrolysis.

## IV. Conclusions

In this work we introduced a concept for producing high strain distributed transducers from soft planar smart materials. The proposed methodology allows to produce simple, miniaturizable, economically affordabe actuation and sensing systems with high transducer counts and densities, that are expected to enable novel applications ranging from highly controllable manufacturing systems to soft robots, medical devices and drug-delivery systems. We experimentally investigated implementation of the distributed actuation unit elements that convert the bending of the smart material substrate into linear displacements normal to material surface. Despite several challenges in implementation, the experiments proved feasibility of the proposed actuation concept. The results showed that the proposed designs are capable of producing large strains, with greater than 2 mm displacement range, and can be further miniaturized.

We therefore have demonstrated our distributed transducer concept feasible. Design optimization and material processing techniques require further investigation, and will be addressed in our future work, along with other functional unit designs (e.g. tilting and rotations) and materials for realization, such as dielectric elastomers and piezopolymers.

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