A Linked Manipulator with Ion-Polymer Metal Composite (IPMC) Joints for Soft- and Micromanipulation

Maarja Kruusmaa, Andres Hunt, Andres Punning, Mart Anton, Alvo Aabloo

Abstract—**IPMCs are electroactive materials that bend in electric field. This paper describes a linked manipulator using IPMC joints. We argue that this design reduces the control complexity of an IPMC manipulator and increases the precision of the device. The design rationale stems from our theoretical work in material modeling. It suggests that when electrically decoupled short IPMC strips are connected to rigid links, the control of the IPMC manipulator, which is currently vaguely understood and highly non-linear, can be reduced to simple inverse kinematics serial chain manipulator control without the loss in efficiency. We validate our design by comparing the prototype device to a simple IPMC manipulator commonly investigated in the literature. The results show increased precision, reaction time and reachable workspace. We suggest that such a manipulator is suitable for soft and micromanipulation.**

I. INTRODUCTION

ELECTROACTIVE polymer materials are materials that change their shape and size when electrically stimulated. This paper describes a manipulator design using a specific type of electroactive polymers, called ionomeric polymer metal composites (IPMC) [1]. These materials bend when electric voltage is applied.

Fig. 1 shows a typical response of an IPMC material to electric stimulation.. When low voltage is applied to the contacts the material bends in response to the stimulation as it is shown in Fig. 1 (A) and Fig. 1 (C). The direction of bending depends on the polarity of the applied voltage.

An IPMC consists of a thin ion-exchange polymer membrane covered with a thin metal layer from both sides. The metal layers serve as surface electrodes. The ion-exchange membrane contains and excess of free cations. When voltage is applied to the surface electrodes through the clamps, the cation migration in the electric field causes the expanding of the membrane from one side and this is observed as bending of the material [2].

IPMC materials work at low voltages (up to 5V), have high actuation length (for example bending radius of 1 cm), they are soft and flexible but at the same time have low output force (few mN). Compared to many other types of electroactive polymer materials IPMCs are also rather mature, with custom-made materials commercially available for purchase [3].

IPMC materials can also work as sensors, when they are mechanically bent they generate voltage between the metal surfaces (few mV) and are proposed to be used as accelerometers or vibration sensors.

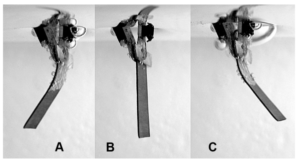

Fig. 1.The IPMC material under electric stimulation

A. *State-of-the-art of IPMCs for robotics*

IPMC materials propose an appealing alternative in robotics design. Devices using the conventional technology of electromechanical devices need rigid links to connect the rotating joints, gears and bearings and they are therefore unavoidably complex, rigid and noisy.

IPMC materials offer almost complementary alternatives to the electromechanical devices. They are lightweight, soft and flexible, noiseless, easy to miniaturize, and permit distributed actuation and sensing. However, compared to the technology of electromechanical devices, they have many drawbacks typical to developing technologies such as high energy consumption and lack of well-established control methods.

To demonstrate their suitability for robotics many proof-of-concept prototype devices have been created, such as a tadpole robot [4], snake like actuators [5] a prototype walking robot [6] or a ray-like underwater robot [7].

B. *IPMC materials for soft manipulators*

Due to the softness and flexibility but small output force, IPMC materials seem to be a natural choice for soft- and micromanipulation. However, there are several fundamental problems still to be solved before these devices could be put in a practical use. First of all, although the material properties of IPMCs are steadily improving, their long-terms stability, efficiency and reliability is still not sufficient for commercial applications. Second, appropriate control methods and mechanical design of these manipulators are still to be developed.

So far, IPMC manipulator design and control is addressed by several authors who also mention soft manipulation as a

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suitable application area. In [8] a higher number of degrees of freedom of IPMC manipulator is achieved by laser ablation of the metal coating of the IPMC strip. There have also been attempts to couple laser patterned sensor and actuator segments on a single piece of a patterned polymer backbone [9]. Zheng et al. have developed a combined IPMC/PVDF sensing actuator and demonstrated its applicability for open-loop micro-injection of living Drosophila embryos [10].

Control of IPMC manipulators is usually investigated in the cantilever beam configuration, fixing one end of a thin IPMC strip between electric contacts and controlling the displacement or the blocking force of the tip [9]. Typically these methods are accurate only at small curvatures, for example, when measuring the output force of a cantilever IPMC actuator against a fixed load cell.

Control of IPMC devices has also been addressed in various papers; none of the results are though particularly successful. For example the walking robot with IPMC linear actuators with the feedback from off-board camera has been reported to walk 6 steps [6]. In our own previous work we have managed to balance and inverted pendulum with an IPMC actuator for 10 seconds [11]. These results are not particularly impressive from the control perspective and rather confirm that the control of IPMC devices is still to a large extent and unsolved problem.

In this paper we propose a design concept of a linked manipulator with IPMC rotating joints and passive links [12]. This design concept is derived from our previous work in material modeling. We argue that this design reduces the control complexity of an IPMC manipulator and increases the precision of the device. The closest related work is reported in [8] where also a multi-DOF manipulator is modeled, but the higher number of degrees is achieved with laser ablation of a single IPMC strip.

II. IPMC MATERIAL MODELLING

A. *Electromechanical modeling of an IPMC manipulator*

IPMC materials can be described by a distributed model shown in Fig. 2 [13]. The resistors *Ra* and *Rb* represent the electrode surface resistance and the resistors *Rc, Rx* and *C* are properties of the polymer ion-exchange membrane.

The circuit shown in Fig. 2 is well known in circuit theory and, in fact, represents a lossy transmission line. Looking at the IPMC manipulator in such a way also explains why real-time control of IPMC manipulators is so challenging.

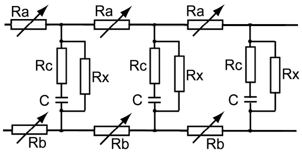

Fig.2. A distributed model of IPMC

The control signals traveling along the transmission line get delayed and distorted. The longer is the line or the larger is the surface conductivity *Ra* and *Rb*, the harder is the behaviour of the actuator to describe. The time-dependent voltage along the line $U(x,t)$ is determined by a homogeneous, constant-coefficient, second-order partial differential equation (a so called diffusion PDE):

$$\frac{\partial U(x,t)}{\partial t} = \frac{1}{(R_a + R_b)C} \cdot \frac{\partial^2 U(x,t)}{\partial x^2} \tag{1}$$

If the transmission line is non-uniform, the closed-form solutions are available only in rare circumstances, the solutions are usually numerical approximations and not necessarily suitable for real-time control.

An IPMC actuator can be described as an open-ended transmission line having a finite length *L*. The voltage along an open-terminated finite-length uniform RC transmission line under step-voltage excitation is solvable in a closed form and is given by the following formula:

$$\begin{aligned} U(x,t) = \sum_{n=0}^{\infty}((-1)^n \cdot (erfc((2n+\frac{x}{L}) \cdot \sqrt{\frac{(Ra+Rb)\cdot C}{4t}}) + \\ erfc((2n+2-\frac{x}{L}) \cdot \sqrt{\frac{(Ra+Rb)\cdot C}{4t}}))) \end{aligned} \tag{2}$$

Here Ra, Rb and C are the total resistance and capacitance of the transmission line with the length L, and $erfc(x)$ is the complementary error function.

The deformation of an IPMC actuator is caused by the relocated ions, equivalent to current through the capacitors *C* in the distributed model.

The general relationship between the curvature k and current through the polymer exchange membrane can be given as

$$k(x,t) = K\int_0^t I(x,\tau)d\tau \tag{3}$$

$I(x,t)$ is time-dependent current along IPMC and *K* is the coupling coefficient measured experimentally. In general, the transmission line causes the input signal to get delayed and progressively weaker when traveling towards the tip and such a behavior is usually hard to describe, analytical solutions exist only for special cases and the solutions are not suitable for real time control.

However, our simulations show that until a certain short length the relationship between the input voltage and deflection angle is linear. So if short pieces of IPMC are considered, there is a chance that the behaviour can be described by a simple formula suitable for real-time control.

To demonstrate this concept we present simulation results of a 3mm long and a 30 mm long IPMC strip. We used the parameters found in previous work [13] *Ra*=3Ω/m, *Rb*=0.45Ω/m, *C*=0.015F/m. These parameters were substituted to (2) and (3) to demonstrate the behaviour of the IPMC in time-space.

From the simulations of the 30mm long strip it is easy to see how the IPMC sheet behaves as a transmission line. When the voltage is applied then it spreads along the sample during 0.5 s. The current through the ion-exchange membrane causes the deformation of the material as described by (3). Therefore the motion of the sheet gets suppressed and delayed towards the tip.

Next, we simulated the behavior of the IPMC strip at short length. The simulation results of a 3mm long sheet, on the other hand, show that the maximal curvature is reached in 0.05 s while the behaviour of *U* and *k* is linear in time and space.

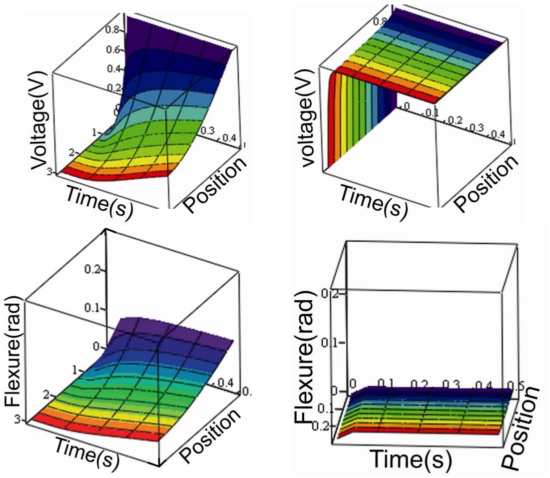

Fig.3. Simulations of flexture and voltage of a 30mm long (left) and 3mm long IPMC sheet (right)

B. *Mechanical modeling of an IPMC manipulator*

In [14] we have presented the mechanical model of the cantilever beam IPMC actuator where the actuator is described as subject to bending caused by an external force and an electrically induced bending moment

We have also investigated a case where the stiffness of the beam is not constant, which makes it possible to analyze cases where part of the IPMC actuator is replaced with a passive rigid elongation.

The theoretical analysis confirmed by experiments has lead to the following conclusions. First, the output force of the actuator is proportional to the width of the IPMC sheet.

It appears that part of the IPMC actuator can be replaced with a rigid elongation and the actuator still has an equal performance in terms of force and deflection. As in [15] the deflection of the IPMC joint is amplified by the rigid extension to match the deflection of the long IPMC sheet. It is also argued in [15] that the rigid extension increases the energy density of the IPMC joint.

Third, the position-force relationship of a short IPMC actuator with an elongation is linear while for an equally long IPMC sheet it is not. From the control point of view, this indicates that an elongated actuator should lend itself better to traditional control methods which assume linearity.

Also, to estimate the shape of the long sheet is more difficult. Fig. 4 shows the static equilibrium states of the two actuators and shows that in the static equilibrium state the shape of the sheet differs. In case of a long sheet the difference is big. In case of a short sheet with a passive rigid elongation the difference is barely noticeable.

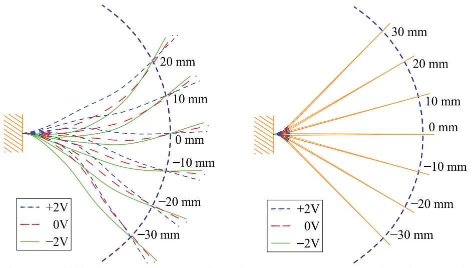

Fig.4. Static equilibrium states of a long IPMC manipulator (left) and a short IPMC manipulator with a rigid elongation (right)

III. MANIPULATOR DESIGN

A. *Design rationale*

The theoretical results in material modeling have guided our design considerations. The conclusions we can draw from out theoretical work re the following:

1. An IPMC material can be described as a lossy RC-line. The longer is the actuator, the longer is the line. The longer is the line, the more the signals get distorted and delayed and the harder the actuator is to model and consequently, to control [13].
2. An IPMC cantilever actuator can be partially replaced with a passive elongation without the loss of actuation force [14].
3. The output force of the actuator does not depend on the length of the IPMC sheet but on the width. When more output force is required, the IPMC actuator should be wider, not longer.
4. If a long strip of an IPMC is replaced with a short IPMC and a passive elongation with an equal efficiency, the mechanical model of the actuator gets simplified. The force-position relationship gets linear and the shape of the actuator is more predictable (see Fig 4).
5. Until a certain short length of the IPMC delay line, the relationship between voltage and deflection angle of the actuator is linear.

These conclusions quite well guide the choices of a manipulator that would be better controllable but still efficient.

First of all, we conclude that a soft IPMC manipulator as it is usually described and analyzed so far by various authors [16,17] can be replaced by a short IPMC piece with a rigid elongation. This would increase the controllability of the manipulator. If the IPMC part is very short with respect to the elongation, the manipulator can be described and analyzed as consisting of a passive rigid link and an active rotating joint. (see Fig. 5)

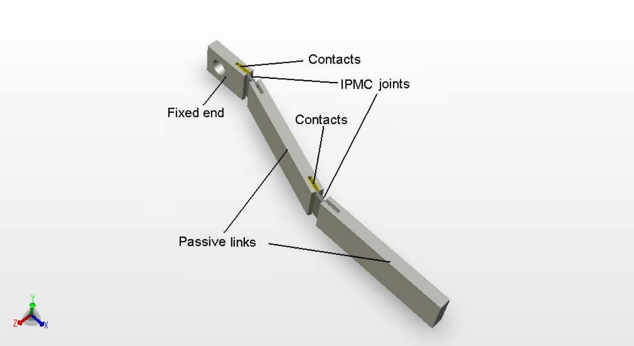

Fig. 5. The design concept of the linked manipulator

When more degrees of freedom are required these joints and links can be liked together to form a chain. Occasionally, this configuration is exactly a classical serial robot manipulator with very well established models and control methods. We can thus reduce the very complicated problem of IPMC manipulator control to the conventional serial robot manipulator control.

At the same time, this design has several advantages compared to traditional robot manipulators where the joints are driven by electric motors. First, this design is mechanically simpler, as it only requires sheets of different materials to be connected together and each joint to be separately powered. Therefore the manipulator is easier to miniaturize. However, it should be also mentioned, that on the other hand, the mechanical design gets more complicated when compared to an IPMC manipulator made of the single strip of an IPMC sheet (such as in Fig. 1).

Second, the manipulator is inherently compliant due to the elastic joints. These would make the manipulator more suitable for soft object and micro manipulator than the conventional electromechanical robotic manipulators where the compliance is achieved with a sophisticated mechanical design and control algorithms.

Compared to the conventional manipulators, the internal friction and inertia are small and therefore the output force is proportional to input voltage which simplifies force control. When designing the manipulator the maximum output force can be determined depending on the application at hand and then the width of the IPMC joints is chosen knowing that the maximal force is proportional to the width of the IPMC joint. In practice, the lack of force control or in general, imprecision of control, can also be somewhat compensated by the inherent compliance of the IPMC material.

IV. VALIDATION OF THE MANIPULATOR DESIGN

We designed a manipulator prototype based on the considerations descried above. The prototype device is depicted in Fig. 6. The length of both links is 30mm. In this section we validate the robot design to justify our design considerations. We aim at answering the following questions:

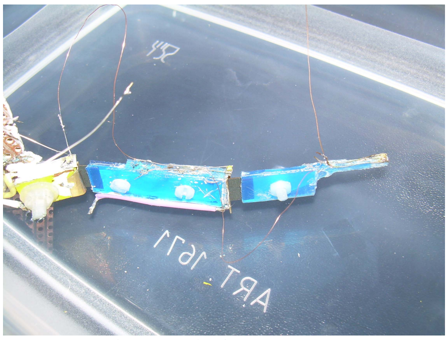

Fig.6. Manipulator prototype

1. Does this manipulator design increase the precision with respect to the conventional manipulator made of a single strip of an IPMC material?
2. Can the input voltage and curvature relationship of a short IPMC joint be described by a linear approximation as suggested by our simulation results in Fig.3?
3. Does the new design of the manipulator increase the reaction time compared to the manipulator made of a single long IPMC sheet as suggested by simulations in Fig.3?

A. *Materials and Methods*

The experiments consist of the following phases:

1. First, a single IPMC joint with a rigid elongation is characterized to find the relationship between the driving voltage and deflection angle.
2. The manipulator is built and tested. The previously gained voltage-deflection angle relationship is used to control the joints. The precision of the manipulator is measured and verified against a single IPMC strip with an equal length.
3. The reaction time to reach the maximal deflection angle is measure and compared in case of a linked manipulator and an IPMC strip.

In the following we briefly describe the experimental setup for each of the experiments, more technical details are available in [18].

Fig.7 shows the general experimental design. The manipulator is driven with LabView7 and from a separate energy source through a current amplifier. The motion of the actuator is recorded with an overview camera. For the single IPMC joint calibration the angle of the elongated strip is recorded against an illuminated white background. To measure the position of the manipulator, LEDs are mounted at manipulator joints.

The IPMC material used in these experiments is

Musclesheet™, provided by BioMimetics Inc. Musclesheet™ consists of a 0.2…0.5 mm thick proprietary ionomer, similar to Nafion, covered with platinum electrodes. The materials were doped with Li^+ or Na^+ counter-ions prior to the experiments and the experiments were conducted in deionised water to keep the environmental conditions constant. The passive links are made of plastic. The length of the manipulator is 66mm. Comparative experiments are conducted with 30mm long IPMC strip (such as in Fig. 1). The width of joints and the long strip is 14mm.

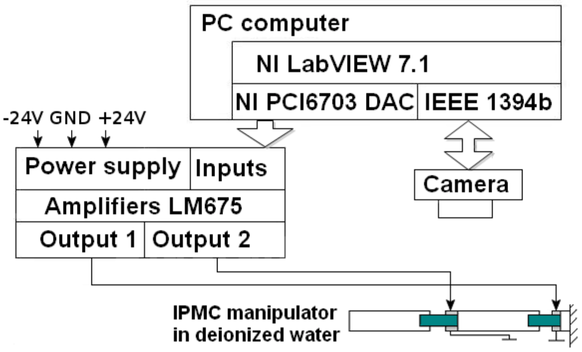

Fig. 7. Experimental setup

B. Characterization of a manipulator segment

The joints of the manipulator where separately characterized using the setup in Fig. 7. The purpose of the calibration was to find the relationship between the driving voltage and the angle of the IPMC joint. Moreover, we were also interested if we can find a certain length of the IPMC joint where the function of the curvature from the input voltage is linear as suggested by simulations in Fig. 3. Assuming that the width of the links is equal with the IPMC joints, all the forces are proportional with the width of the IPMC joints. Hence the width of the sheet does not influence the deflection angle.

Some results of the joint calibration are found in Fig. 8. It shows the calibration results of the IPMC joint with a length resulting to linear behaviour and of another one, which is non-linear.

The results show that it is possible to find a length of an IPMC joint where the voltage-angle relationship can be described by a simple analytical linear function which simplifies control of such a joint. This length was 4mm±2mm in this case, varying along samples. These results are consistent with our simulation results in Fig. 3.

C. Reaction time

Next we recorded reaction times of the linked manipulator and an IPMC strip. The two manipulators where controlled in the same way. The voltage was applied to both devices and the time required to obtain the maximal curvature was recorded. The results show that the reaction time of a long sheet is 0.5 sec longer than of the manipulator. This behaviour is also visible in the simulations in Fig. 3 where it is seen that the sheet motion is surprised and delayed towards the tip. In our case the inertial forces are much smaller than viscose resistance and hence can be neglected.

D. Manipulator control

The purpose of the experiments with the manipulator was to show that the linked manipulator with IPMC joints can be reduced to a simple serial link robotic manipulator and be controlled using simple methods of inverse kinematics.

The joint and tip positions where then extracted from a camera image. The precision of the manipulator was then measured by choosing 400 random points from the workspace of the manipulator and driving the tip of the manipulator to reach these goal points. The manipulator was driven by LabView 7 calculating the joint angles with inverse kinematics equations. In case of a planar manipulator with 2 joints these equations reduce to simple trigonometric equations. The driving voltages corresponding to the angles where found using the calibration described above.

Our aim was to compare the control precision of the linked manipulator to a single IPMC strip. For that purpose we used a single IPMC strip with the length equal to the length of the link of a linked manipulator. We characterized the strip by curve fitting as we did for the joints of the linked manipulator. Next, we chose random points on the working trajectory of the manipulator, as we did for the linked manipulator and measured the precision of the open-loop control.

In Fig. 9 the errors of the linked manipulator and the IPMC sheet are shown measured in Euclidian distance between the desired and actual end points. The mean error of the linked manipulator is 1.14mm (stdev 0.92) and the IPMC strip is 3.59mm (stdev 2.20mm) which means that the precision of the manipulator has increased by 314%.

V. CONCLUSIONS

This paper presented a linked manipulator with IPMC joints. The main contribution is to show that the IPMC manipulator control, very vaguely understood so far, can be reduced to simple well-established methods of inverse kinematics. Although serial chain manipulators are a standard measure in robotics this kind of a solution has not been investigated for IPMC actuators. The rationale for this design is not "to build the manipulators like it is always done" but is motivated from our theoretical work in materials modeling. This work theoretically shows that the behavior of a short IPMC manipulator is more linear and that part of the IPMC actuator can be replaced by a passive elongation without the loss in efficiency. Our experimental results confirmed these assumptions. The precision of the linked manipulator increased 314%, the reaction time 0.5 s

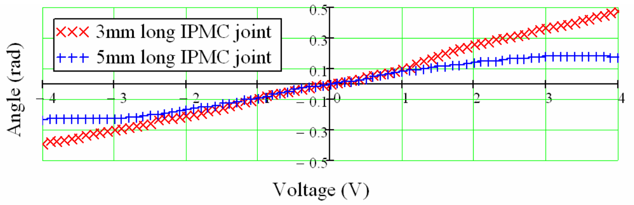

Fig. 8. Calibration results of 3mm long IPMC joint, where the voltage-angle relationship is linear (red) and 5mm long joint, where it is non-linear (blue).

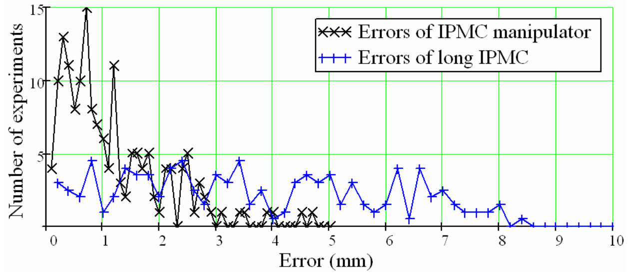

Fig. 9. Errors of the linked manipulator and the long IPMC strip. For convenience the errors are represented in Euclidian distance (the actual measurements were recorded for x and y coordinates separately where they also follow the Gauss distribution).

and we found a length of an IPMC joint (3mm) where the voltage-angle relationship can be described by a linear function. The workspace also increases from a circular trajectory to 2D.

The parameters of IPMC material samples may vary considerably and we therefore do not expect the quantitative results to hold when the experiments are repeated with different IPMC materials. For example, if the surface resistance is lower, the length and reaction time is increased and a larger actuation length would increase the workspace.

This design can be improved or modified for example by adding more links to even more increase the workspace, to change the orientation of joints to make the manipulator to work in 3D instead of 2D or by adding an extra soft link to the tip of the manipulator for extra soft manipulation.

This work only addresses the open-loop control of the manipulator. However, it has several implications to close loop control. By decreasing electrical and mechanical hysteresis and characterizing the manipulator with linear relations between the input voltage and curvature or output force we expect that the system can be described as a linear time invariant system and therefore becomes easier to be controlled in a closed loop. Furthermore, it is well known that IPMC materials also have sensor properties [17,19]. In our own previous work we have described a self-sensing actuator that could be used to build and control self-sensitive IPMC joints [20].

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