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Possible design/fabrication of a soft biomimetic magic (flying) carpet made with Ionic Polymer Metal Composites (IPMCs)

Abstract

A novel design of an artificial soft robot similar to the motions of a magic carpet is presented. Reported in the planning, designing, and fabricating of a biomimetic magic (flying) carpet made with ionic polymer metal composites (IPMCs). A new family of IPMC sensors and actuators is proposed to be used as a flexible plate and a flexible carpet to form a biomimetic flexible soft sensor and actuator system. The magic carpets made with IPMCs will be experimentally capable of bending, rolling, turning, twisting, and simultaneous sensing. However, their sensing characteristics as a soft biomimetic magic carpet feedback sensor are shown to have great potential for ubiquitous robot-human interactions (RHI). Upon various types of deformation, they are shown to generate uniqueoutput voltage signals and transient currents to be correlated to the actual magic carpet feedback force. Furthermore, a flexible sheet of IPMC can be actuated simultaneously on the fly by a small power supply embedded in the magic carpet. The magic carpet version of IPMC can be applied as smart skin to develop human-like dexterous and soft manipulation.

Keywords: IPMCs, magic carpet, soft robotics

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Introduction

This paper introduces a possible design for an IPMC magic carpet with soft actuation andsensing in a flexible plate configuration. Shahinpoor, Bar-Cohen, Xue, Simpson, and Smith[1–2] published an early version and review of IPMCs in 1998.[1–2] See the pioneering works of Osada, Oguro, Kawami, Asaka, Takenaka, and Shahinpoor[3–14] to see their pioneering work in the 1992-93 period. The electrodynamics of cations generation and transportation in IPMCs are governed by the Poisson-Nernst-Planck field equations.[15–27] Biomimetic soft robotic actuation like artificial muscles and sensing of these materials display artificial muscle behavior.

The paper shows only the simulation results and does not provide a detailed theoretical analysis. It must be emphasized that achieving sustained flight with a soft biomimetic flying carpet made of IPMCs can be quite challenging due to the power andenergy requirements. IPMCs typically require a voltage to induce deformation and sustain flight significantly, which may demand substantial power sources or energy storage systems. Meeting these power and energy requirements while maintaining thesoft and flexible nature of the carpet can be a serious limitation.

Soft materials like IPMCs may exhibit nonlinear and time-varying behavior, making it challenging to develop robust control algorithms. Ensuring stable and maneuverable flight with accurate position and altitude control is a complex task thatrequires careful design and control strategies.

Note that payload capacity: A soft biomimetic flying carpet made with IPMCs may belimited. IPMCs are relatively lightweight and have limited load-bearing capabilities. Thislimitation can restrict the transportation of significant payloads or equipment, which may be essential for certain applications.

Actuation and sensing configurations

IPMCs, as shown in Figure 1, undergo similar cation migrations and rearrangements when subjected to either an electric field or a deformation field. Small samples of IPMC cantilevered strips (0.5cmx3cmx0.2mm) can generate a tip-blocking force density equalto 40. This capability means they can lift an object 40 times its weight.[12,23] For example, if the weight of an IPMC strip with a density of 2 gm/cm3 is 0.1 gmf, it can produce a tip-blocking force of about four gmf.

Several water molecules tend to attach or bond with cations. This is called the hydration number: 4 for Na+ and 6 for Li+. Poisson-Nernst-Planck phenomena[23,24] govern such ion dynamics, which we will not consider theoretically in this short paper. Artificial Soft Robotic Magic Carpet made with (IPMCs): The idea of designing and operating a soft biomimetic, highly maneuverable robotic arm like a magic carpet is highly desirable for many soft biomimetic robotic applications.

Alternatively, On the other hand, if such deformations are physically applied to anIPMC strip, they generate an output voltage signal (a few millivolts for typical small samples (5mmx30mmx0.2mm) as sensors and energy harvesters.

They have a force density of about 40 in a cantilever configuration with typical sizesof mmx30mmx0.2mm, meaning they can generate a tip force of almost 40 times their weight in a cantilever mode. In this case, the weight of the cantilever is about 0.06 gmf based on a density of 2 gm/cm3 for IPMCs, which means it can produce a tip-blocking force of 2.4 gmf.

Thus, such a typical sample of IPMCs in actuation, sensing, and energy harvesting modes has a very broad bandwidth to kilo HZ and higher. IPMCs were introduced in 1998 by Shahinpoor, Bar-Cohen, Xue, Simpson, and Smith.[1,2] However, the original idea of ionic polymer actuators and sensors goes back to 1992-93 results by Osada et al.,[3] Oguro et al.,[4,8,10] Adolf et al.,[9] and Shahinpoor.[6]

The essential mechanism for IPMCs' actuation and sensing/energy harvesting capabilities is the migration of cations (Na+, Li+), which are loosely adjoined to the underlying molecular network with anions, towards the cathode electrode and away from the anode electrode due to either an imposed electric field (actuation) or an imposed deformation field (sensing/energy harvesting).

Figure 1 graphically displays the actuation and sensing mechanisms in cantilever stripsof IPMCs. Thus, this scenario forces the strip to bend accordingly. Note that if the electrodes are not placed symmetrically on the IPMC strip, they can bend and twist, as shown in Figures 2a and 2b. Figures 2a and 2b depict the deformation of typical small strips of IPMCs (4cmx1cmx0.2mm) in a small electric field (voltage of 4 volts) or 20kV/m.

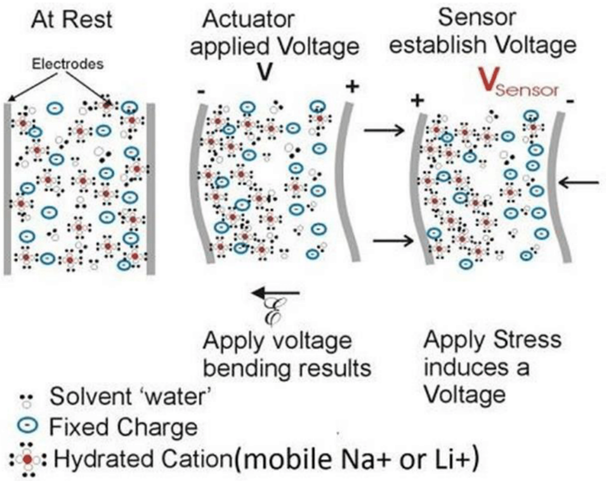
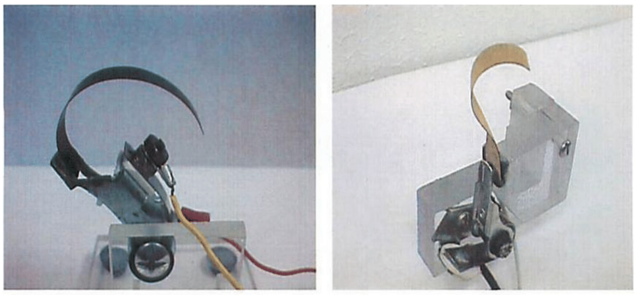


Figure 1 Essential mechanisms of actuation and sensing in IPMCs.



(a) (b)

Figure 2 Deformation (bending, (a), bending & twisting, (b)) of typical small strips of IPMCs (4cmx1cmx0.2mm) in a small electric field of 20kV/m.

Figures 3 and 4 depict typical graphical displays of the deformation of IPMC strips in acantilever configuration versus voltage and current both in actuation and sensing modes.

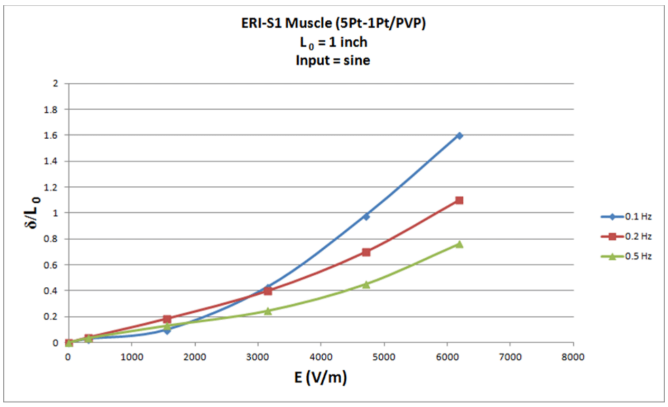


Figure 3 Non-dimensional IPMC cantilever (1cmx4cmx0.2mm) tip deflection versus the imposed sinusoidal electric field for three different frequencies (0.1-0.5 Hz).

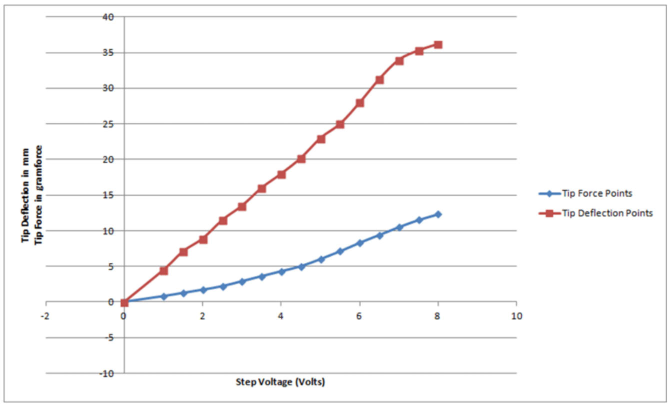


Figure 4 IPMC cantilever (1cmx4cmx0.2mm) tip deflection and tip blocking force versus the imposed step voltage.

Figures 3 and 4 depict typical graphical displays of the deformation of IPMC strips in acantilever configuration versus voltage and current both in actuation and sensing modes. Figure 5displays an IPMC cantilever (1cmx4cmx0.2mm) in a sensing/energy harvesting mode showing tip deflection versus output oscillatory voltage signal.

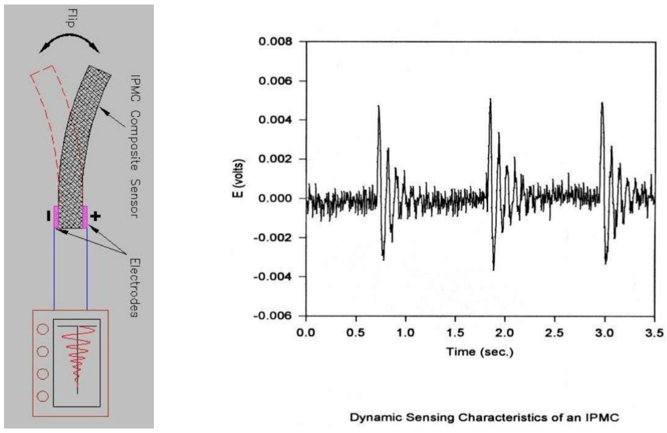
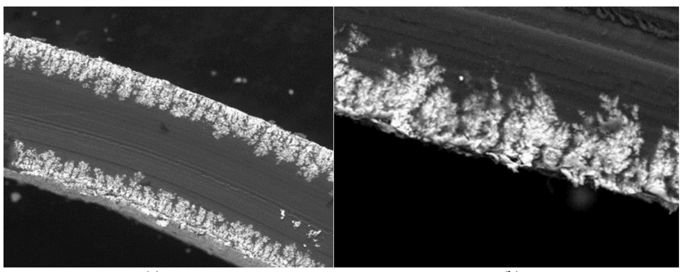


Figure 5 IPMC cantilever (1cmx4cmx0.2mm) in a sensing/energy harvesting mode showing tip deflection versus output oscillatory voltage signal.

The IPMCs are essentially manufactured by a chemical REDOX operation in which the ionic polymer is initially surface treated to increase its surface density for molecular diffusion andelectroless plating and then oxidized by molecular diffusion of a metallic salt and then reduced byplacing it in a reduction solution such as sodium borohydride to generate Na+ cations and furthercreate fractal nanoclusters within the molecular network near boundary, as shown in Figure 6a and 6b.



(a) (b)

Figure 6 SEM picture of a typical IPMC thin strip showing the near boundary electrodes (a) and penetration of reduced metals in a fractal manner around nanoclusters within the material (b).

The IPMCs are a two-phase system comprising a polar medium such as water. They contain ion cluster networks surrounded by an ion-containing hydrophobicpolytetrafluoroethylene (PTFE or Teflon). The structural stability of the ion-containing polymer is provided by the PTFE backbones and the hydrophilic clusters, which facilitatethe transport of ions and hydrated water molecules attached to them in the ionic polymer.

These nanoclusters (3-5 nanometers) contain an interfacial region of hydrated, sulfonate-terminated perfluoro ether side chains surrounding a central region of polar fluids with cations such as Na+ or Li+.

As reported by Shahinpoor and Kim,[11] Shahinpoor, Kim, and Mojarrad,[12] and Kim and Shahinpoor,[13-14] ion-containing polymers in a nano-composite with a conductor phase can be manufactured three-dimensionally to any complex shape as, for example, helical or magic carpet coil, as shown in Figure 7. Figure 7- A coil-type ionic polymeric nano-composite with gold electrodes for linear nanosensing and nanoactuation.

Figure 7 A coil-type ionic polymeric nano-composite with gold electrodes forlinear nanosensing and nanoactuation.

Novel family of IPMCs as magic flying carpet

Magic carpet IPMCs can be assembled as wavy sheets, as shown below in Figure 8, toform a magic carpet with a feedback sensor and magic carpet actuator, as shown in Figures8 (a, b, c, d). The magic carpet cantilever IPMCs can bend and twist actuation and soft sensing.

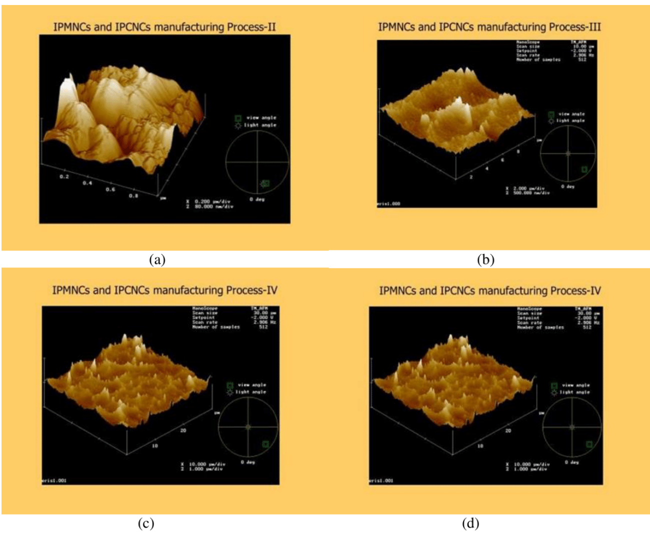


Figure 8 Various IPMCs (a, b, c, d) resembling the deformation of a flying carpet.

Let us consider a specific design for a biomimetic electrically deformable capable of generating wavy motion for the magic carpet made with strips of IPMCs as shown belowin Figure 9 (a, b, c, d, e and f) and similar to the wavy motion of a typical magic carpet.

For the proposed magic carpet to maneuver, Figure 9-A shows the number of configurations f (a, b, c, d, e, f, g, h) or the magic carpet made with IPMC artificialmuscles.

Note in Figure 9 that this is just a simulation and not real operational data. However, this is a good start toward making a flying magic carpet.

Let us consider a specific design for a biomimetic electrically deformable capable of generating wavy motion for the magic carpet made with strips of IPMCs as shown below in Figure 9 (a, b, c, d, e and f) and similar to the wavy motion of a typical magic carpet.

For the proposed magic carpet to maneuver, electrodes should be attached in a cross-hatched configuration to allow local bending, as shown in Figure 9 (a, b, c, d, e, f, g, h), which shows the number of configurations f (a, b, c, d, e, f, g, h) or the magic carpet made with IPMC artificial muscles.

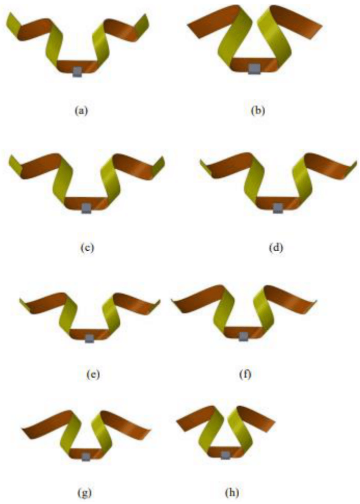
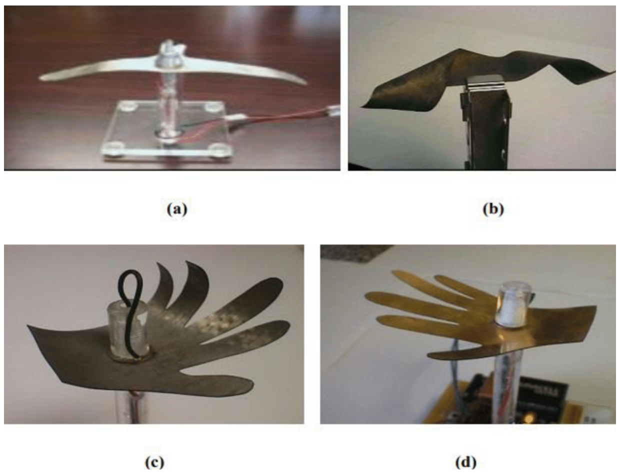


Figure 9 A number of configurations f (a, b, c, d, e, f, g h) or the magic carpet madewith IPMC artificial muscles.

Figures 10 (a, b, c, d) depict some configurations for the **magic carpet operations**.



Figures 10 a, b, c, and d show some configurations for the magic carpet operations.

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Design details

The magic carpet can be designed with printed electrodes on both sides of the carpet, asshown below in Figures 11a and 11b.

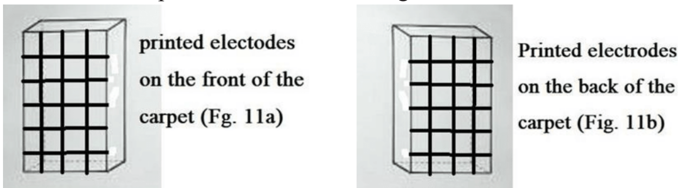

Figure 11 Design of magic carpet with printed electrodes on both sides that actively bend locally to create the carpet's wavy motion.

Note from Figures 1 and 6 how these printed electrodes can be energized to deform the carpet locally and create local curvature during flight a shown in Figures 2, 7, 9 and 10.

IPMC Modeling and simulation

Here, we present a very brief review of the mathematical modeling of the dynamic deformation of the magic carpet. Gennes and coworkers[17] presented the first phenomenological theory for sensing and actuation in ionic polymer metal composites. Asaka et al.,[18] discussed the bending of polyelectrolyte membrane-platinum composites by electric stimuli and presented a theory on actuation mechanisms in IPMC by considering the electro-osmotic drag term in transport equations. Let us now summarize the underlyingprinciple of the Ionic polymeric nanocomposite actuation and sensing capabilities, which can be described by the standard Onsager formulation using linear irreversible thermodynamics. When *static conditions* are imposed, a simple description of the *mechanoelectrical effect is possible based upon two forms of transport: ion transport (with a current density, normal to the material) and solvent transport (with a flux; we can assumethat this term is water flux*). The conjugate forces include the electric field and the pressure gradient. The resulting equation has the concise form of,

$$\underset{\sim}{J}(x,y,z,t) = \sigma \underset{\sim}{E}(x,y,z,t) - L_{12} \underset{\sim}{\nabla} p(x,y,z,t) \quad (1)$$

$$\underset{\sim}{Q}(x,y,z,t) = L_{21} \underset{\sim}{E}(x,y,z,t) - K \underset{\sim}{\nabla} p(x,y,z,t) \quad (2)$$

where σ and K are the material electric conductance and the Darcy permeability, respectively. A cross coefficient is usually $L = L_{12} = L_{21}$. The simplicity of the above equations provides a compact view of the underlying principles of actuation, transduction, and sensing of the ionic polymer nanocomposites. When we measure the *direct* effect (actuation mode), we work (ideally) with electrodes impermeable to ion species flux, and thus we have $\underset{\sim}{Q} = 0$. This gives:

$$\underset{\sim}{\nabla} p(x,y,z,t) = \frac{L}{K} \underset{\sim}{E}(x,y,z,t) \quad (3)$$

This will, in turn, induce a curvature proportional to $\underset{\sim}{\nabla} p(x,y,z,t)$. The relationships between the curvature and pressure gradient are fully derived and described in de Gennes,Okumura, Shahinpoor, and Kim.[17]

Let us mention that

$$(1/\rho_c) = \mathbf{M}(\mathbf{E})/\mathrm{YI} \quad (4)$$

where **M**(**E**) is the local induced bending moment and is a function of the imposed electric field **E**, Y is Young's modulus (elastic stiffness) of the strip, which is a function ofthe hydration H of the ionic polymer metal nanocomposite. **I** denote the moment of inertiaof the strip. Note that locally, M(**E**) is related to the pressure gradient such that in a simplified scalar format.

$$\nabla p(x,y,z,t) = (2\mathrm{P}/t^*) = (\mathbf{M}/\mathrm{I}) = \mathrm{Y}/\rho_c = \mathrm{Y}\underset{\sim}{k}. \quad (5)$$

From equation (4), it is clear that the vectorial form of the curvature is related to theimposed electric field **E** by $\underset{\sim}{k}_E = (\mathrm{L}/\mathrm{KY})\underset{\sim}{E}$. Based on this simplified model, the tip bending deflection $\ddot{a}_{max}$ of an IPMC strip of length l_g should be almost linearly related to the imposed electric field because:

$$\underset{\sim}{k}_E \cong [2\delta_{max}/l_g^{\,2} + \delta_{max}^2)] \cong 2\delta_{max}/l_g^{\,2} \cong (\mathrm{L}/\mathrm{KY})\underset{\sim}{E} \quad (6)$$

The experimental deformation characteristics of IPMCs[19–21] are consistent with the above predictions obtained by the above linear irreversible thermodynamics formulation, which is also consistent with equations 1 and 2 in the steady state conditionsand has been used to estimate the value of the Onsager coefficient L to be of the order of 10^{-8} m^2/V-s. Here, we have used a low-frequency electric field to minimize the effect of loose water back diffusion under a step voltage or a DC electric field. Other parameters have been experimentally measured to be K~10^{-18} m2/CP, $\sigma \sim$ 1A/mV or S/m. Figure 12 depicts a more detailed data set about the Onsager coefficient L.

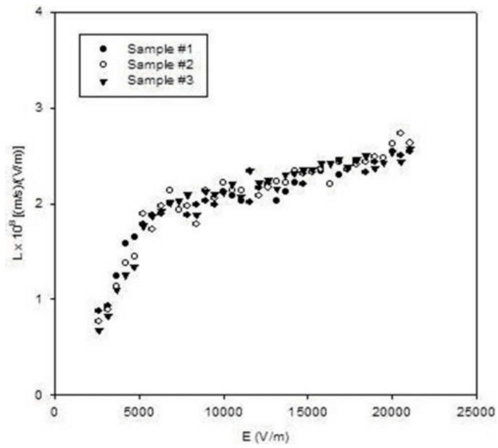

Figure 12 Experimental determination of Onsager coefficient L.

On the other hand, one may consider charge transport modeling of actuation and sensing, which we refrain from performing and refer the reader to Bahramzadeh and Shahinpoor[22,23] and Shahinpoor.[24]

Considering the angled concept or the helical concept, the membranes are at angle α formation. As a result tip displacement would be $\delta_{ver} = \delta \sin\alpha$ in case of flat actuator we have $\delta_{hor} = \delta \cos\alpha$ and for the helical rotation will be $\omega = 2\pi\delta\cos\alpha / D$ in which D is diameter of the actuator. Please note that a good amount of literature here in this paper is already published as depicted in the list of references. However, the unique idea of the possibility of making magic carpets with IPMCs is the essential originality of the current paper.

Eventually, a version of the magic carpet has to be built from IPMCs, and its flying capabilities are demonstrated. It will be a moving and deforming flexible two- dimensional carpet that can aerodynamically suspend itself in the air or water. But thiseffort will be hopefully reported later when the carpet is built and flown.

Conclusion

A possible novel design of an artificial soft robot similar to the motions of a magic carpet was presented. The planning, design, and partial fabrication of a biomimetic magic (flying) carpet made with ionic polymer metal composites (IPMCs) are briefly described. The magic carpets made with IPMCs will be experimentally capable of bending, rolling, turning, twisting, and simultaneous sensing.

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Conflicts of interest

Authors declare that there is no conflict of interest.

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