IONIC POLYMER-METAL COMPOSITES

Wireless actuation and control of ionic polymer–metal composite actuator using a microwave link

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The ionic polymer–metal composite (IPMC), a type of electroactive polymer (EAP) actuator, has created a unique opportunity to design robots that mimic the motion of biological systems due to its soft structure and operation at a low voltage. Although this polymer actuator has strong potential for a next-generation artificial muscle actuator, it has been observed by many researchers that supplying actuation voltages in multiple locations is challenging. In robotic applications, a tethered operation is prohibited and the battery weight can be critical for actual implementation. In this research, the remote unit can provide necessary power and control signals to the target mobile robot units actuated by IPMCs. This research addresses a novel approach of using a wireless power link between the IPMC and a remote unit using microstrip patch antennas designed on the electrode surface of the IPMC for transmitting the power. Frequency modulation of the microwave is proposed to selectively actuate a particular portion of the IPMC where the matching patch antenna pattern is located. This approach can be especially useful for long-term operation of small-scale locomotion units and avoids problems caused by complex internal wiring often observed in various types of biologically inspired robots.

**Keywords:** ionic polymer–metal composite actuator; microwave link; wireless actuation; robotic application; biomimetic robot

1. Introduction

Recent advances in artificial muscle actuators based on electroactive polymers (EAPs) have created a unique opportunity to accommodate greater flexibility and more degrees of freedom to design biologically-inspired robots. The unique properties of biological muscle are large strain, moderate stress, fast speed, good efficiency and long cycle life. A new technology based on polymer science and engineering has enabled EAP to simulate these properties and functions. An ionic polymer–metal composite (IPMC) has demonstrated many new capabilities in robotic actuation technology due to its low-voltage requirement, relatively large deformation and shape-changing capabilities. In particular, the IPMC can be fabricated in various shapes and sizes; with proper intelligent and biomimetic shape-changing control schemes, such as polymeric actuators, the IPMC can offer clear advantages in developing an intelligent biomimetic robotic system over the traditional electromechanical actuators.

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Biomimetics is the concept of taking ideas from nature and implementing them in another technology, such as engineering and design. Future technology will encompass engineering devices that confer the performance advantages of natural systems on a new class of biomimetic machines. Recent research on animal motion has made tremendous progress towards a better understanding of their complex motions [1–6]. Despite this progress, a major shortcoming is the lack of technology that can mimic complex movements and be controlled with a stable power supply source under unstructured environments.

In this research, a wireless actuation scheme of a robot utilizing its versatile body morphology, often seen in the biomimetic system, was studied using an intelligence microwave link. This remote wireless link could be a breakthrough in effective remote motion control that can adapt to a variety of unstructured environmental conditions. Although the IPMC actuator has a strong potential to be the next-generation artificial muscle actuator, it has been observed by many researchers that wiring the power line to a respective electrode surface is challenging, especially during micro-scale actuation and multi-segmented or patterned design [7–10]. There are many robotic applications where tethered operation is prohibited, and a battery weight can be a major obstacle for actual implementation of the robots [11–14]. It is necessary to have a breakthrough in an intelligent power supply and control unit in order to design robust robotic systems that can be adaptable to unstructured and tortuous environmental conditions.

Wireless power transfer is a promising technology for a long-term power supply for wireless applications [15]. Electromagnetic radiation is more efficient than inductive power transfer because it can transmit over long distances; in addition, the size of reception device can be miniaturized. A rectenna is the key component for reception of radiation, and is composed of the rectifying circuit and antenna [16,17]. A space solar power system (SSPS) uses microwave power transmission of 1 to 10 GW electric power, generated in the geostationary orbit to the ground [18]. A long-endurance, high-altitude platform known as SHARP (stationary high-altitude relay platform) receives power from a large array of antennas on the ground [19]. Compared to the above, high-power transmission applications and also a weak-power transmission using a flexible rectenna have been researched [20–22]. The flexible dipole rectenna arrays, built on thin film based flexible membranes, provides the power to the other smart material actuator.

In this research, a novel approach is proposed that uses a wireless power link between the IPMC actuator and its remote power unit. Microstrip patches are patterned on the surface of the actuator’s electrode, and acts as a rectenna. Without the external power wires, controller, and battery, the actuator can be miniaturized, depending on the operating frequency, and can provide uninterrupted power to the actuator. The main contribution of this paper lies in the preliminary study of the wireless power transmission and control method, including (1) microstrip patch antenna design on the electrode surface of the IPMC actuator and (2) selective actuation of different parts of the IPMA actuator by locating frequency-dependent patch antenna patterns at strategic locations.

The paper consists of six sections. Section 2 covers the basic principles of the wireless power transmission technique proposed, and Section 3 covers its application for bending motions of the IPMC actuator. Section 4 discusses multi-frequency microwave for possible application with multi-IPMC actuators. A novel design of the integrated IPMC rectenna is discussed in Section 5, along with computer simulation results as well as experimental results. In Section 6, IPMC materials suitable for use in the rectenna application are discussed.
2. Wireless power transmission

Wireless power transmission is a promising technique for long-term power supply of wireless applications. This research studied a wireless power transfer by means of electromagnetic radiation, as opposed to inductive power transmission. The key component of electromagnetic radiation is a rectenna, which is a combination of a rectifying circuit and an antenna. The antenna receives the electromagnetic power, and the rectifying circuit converts it to electric power. Figure 1 shows a schematic diagram of the rectenna system.

To verify the proposed method for wireless power transmission, several experiments were performed. Figure 2 is a block diagram of the experimental setup, and Figures 3 shows a photo of the devices used. In this experiment, a high-frequency circuit material, RO3003 $^\circ$ [23], was used for the microwave receiving rectenna, and an ionic polymer metal composite (IPMC) was used as an actuator. Specifications of the circuit material are given Table 1. The signal generator, HP 8672A, produced microwave signals ranging from 8 GHz to 12 GHz; this device was controlled by a computer. The traveling-wave-tube (TWT) amplifier, Hughes 1177H, amplified the power of the microwave, and a horn antenna radiated the microwave to the rectenna. The rectenna received the microwave signal and convert it to DC power using a high-frequency rectifying circuit. The IPMC was actuated by this DC power, and the driving voltage was monitored by a digital scope. At the same time, a digital camera, Basler A602i, captured the motion of the IPMC actuator. The power sensor...
was used to measure the microwave power. In the first experiment, the electrical characteristics of the rectenna and the motion of actuator were measured. In the second experiment, the multi-frequency driven multi-actuators were tested.

3. The electrical characteristics of the rectenna and the motion of the actuator

To understand the electrical characteristics of the rectenna and the motion of actuator, a 9 GHz rectenna and the IPMC actuator were used to measure the timed response of the transmitted voltage and its subsequent bending motion. The ionic liquid coated dry type of IPMC actuator was used for experiment, and the length of IPMC actuator is 50 mm and width is 3 mm. Figure 4 shows a prototype of 9 GHz rectenna.

As mentioned in the previous section, the rectenna is the combination of a rectifying circuit and an antenna. At the positive wave, a high-frequency detector diode blocks an incoming wave, and a capacitor and the IPMC charge a positive voltage, as shown in Figure 5a. For a negative wave, the diode passes the negative wave, as shown in Figure 5b. In the first design, the rectenna was designed without a load resistor, as shown in Figure 5d; this resulted in a very slow reverse bending motion due to poor dissipation of accumulated charges in the IPMC even after the applied voltage becomes zero. This is caused by the rectifying circuit’s inherent characteristics of generating only a positive voltage, which makes the actuator bend in only one direction.

To make a reverse directional bending motion, the IPMC actuator must dissipate the charged energy accumulated during a forward bending motion. In this case, the IPMC acts as a charging capacitor. To make the charged IPMC dissipate its stored energy quickly, a load resistor was added, as shown in Figure 5c. With this load resistor added, the time taken
to dissipate the stored charge decreased significantly, and the reverse bending speed was
improved.

Figure 6a illustrates the schematics of the experimental setup, and Figure 6b is the plot
of the measured voltages at various distances from 40 mW microwave source antenna.
To measure the electrical characteristics and its motion generated by the IPMC actuator,
the 40 mW power microwave was radiated to the rectenna with the load, which was placed
10 cm away for 25 s. Figure 7a and 7b show the voltages and subsequent motion of the
actuator before and after the microwave is turned off. Figure 7a shows the voltage profiles
without load and with load (1 kΩ); this demonstrates that the charged voltage dissipates
faster with the load. Figure 7b shows that the reverse x-axis motion of the actuator is faster
than the one without the load. Figure 8 shows the motion of tracked mark position.

From the results given above, it is apparent that microwave transmits a reasonable level
of voltage to drive the IPMC actuator; also, the load resistor in the circuit quickly dissi-
pates the charged power and accomplishes quicker return of the actuator to the original
position. This feature can be useful for generating agile motions of the actuator when it is
implemented on the actual robotic devices.

The single diode rectifying circuit of Figure 6 was improved using a voltage doubler
circuit [24]. As shown in Figure 9, a negative wave C1 capacitor is charged through diode
D1, and the voltage of C1 is added with that of the source for a positive wave; as a result,
charging C2 doubles the source voltage through D2.

Figure 10 shows two rectennas, one with a single diode circuit and the other with a
voltage doubler circuit. Two rectenna antennas were designed for a 8.5 GHz reception
frequency; however, the measured peak voltages were at a frequency of approximately
8.7 GHz. This was caused by an inaccuracy in the milling machining of the antenna
pattern and also by a problem in impedance matching. However, an 8.7-GHz-frequency
microwave signal can be used to control the rectenna. To verify the frequency performance
of therectenna, the output voltages of the rectenna were measured by scanning the operat-
ing frequency from 8 GHz to 10 GHz for a 37 mW source. For the voltage doubler circuit,
output voltage was 0.65 volt and 60 % higher than the output voltage 0.4 V of single diode
circuit, as shown in Figure 11.
Figure 5. Rectifying circuit (a) with a positive wave, (b) with a negative wave, (c) with a load resistor and (d) without a load resistor.

Figure 6. (a) Schematics of the experiment and (b) measured voltage without load and with load using 40 mW power.
4. Multi-actuator control using multi-frequency microwave

One of the unique features of the proposed microwave-based power transmission technique for the IPMC actuator is its capability to control more than one IPMC, with multiple rectennas, by radiating multi-frequency microwave signals with matching frequencies. Figure 12a shows a stacked rectenna, designed for 8.3 GHz and 9.0 GHz frequencies, which can receive a multi-frequency microwave stream. Figure 12b shows the output voltages of the rectenna when the frequency is scanned from 8 to 10 GHz with a 50 mW microwave at 10 cm away from a horn antenna, as shown in Figure 6a. The peak voltage shown in Figure 12b at the 9 GHz corresponds to the resonance frequency of 9 GHz patch rectenna; the other peak at 8.3 GHz is the resonance frequency for a 8.3 GHz patch rectenna. It should be noted that a 0.6 voltage peak shown between 8.5 GHz and 9 GHz is due to an impedance mismatch of the antenna input.

To generate the multi-frequency microwave signal, a signal generator with a general purpose interface bus (GPIB) interface is used for the real-time control of the microwave
Figure 9. Voltage doubler circuit for (a) with a negative wave and (b) with a positive wave.

Figure 10. Rectenna with (a) a single diode circuit and (b) a voltage doubler circuit; (c) the size of rectenna is 10 × 16 mm.

Figure 11. Voltage output of frequency scanning.
Figure 12. (a) Multi-frequency rectennas and (b) the voltage output by frequency scanning.

stream, as shown in Figure 13a. Using the GPIB control command, the 8.3 GHz and 9.0 GHz waves are alternately radiated every 1 s. For the first 20 s, the 8.5 GHz wave is radiated, and 8.3 GHz and 9 GHz waves are radiated alternately for next 20 s. Only the 9.0 GHz wave is radiated for the next 20 s after that. When the 8.3 GHz wave is radiated, the 8.3 GHz rectenna generates the output voltage, and it induces a bending motion for the actuator connected to the 8.3 GHz rectenna. When 8.3 GHz and 9.0 GHz waves are radiated alternatively, both rectennas generate the output voltage and cause both IPMC actuators to move. After 40 s, only the 9.0 GHz wave is radiated. As shown in Figure 13b, outputs of both the 8.3 GHz and 9 GHz rectennas are observed after 20 s; however, the voltage magnitude from the 8.3 GHz rectenna does not go to zero even after the 8.3 GHz microwave is turned off. This can be blamed on an imperfect design of the 8.3 GHz rectenna. In other words, the 8.3 GHz rectenna induces voltage even if only the 9.0 GHz wave is turned on. When a rectenna is designed and fabricated, ideally it must respond to a particular frequency only. However, this frequency-isolation characteristic of the rectenna often is imperfect due to fabrication procedures.

After both waves are turned off, the voltage charged in the capacitor and IPMC is dissipated so that the IPMC actuator can return to the original position. Another important observation is that possible noise sources are from the frequency range of 9 GHz microwave and a DC voltage at rectifier. For the 9 GHz microwave, the possible sources are a satellite broadcasting band (9–12 GHz) and a cell phone band (850 and 1900 MHz), but we can ignore the effect of both sources since the satellite broadcasting signal is too weak to be considered and the cell phone band is in a different range. At the DC range, the ground of the DC power was isolated to eliminate any possible noise.

In the Figures 11 and 12b, the output voltage fluctuation from the rectifier is due to nonlinearity of size and parameters of the rectenna patch used in the experiment. The fluctuation patterns on the DC output of the rectifier shown in Figure 13b is mainly from the way how dual frequency (8.3 and 9.0 GHz) microwaves are transmitted from a single power source using the time division multiplexer (TDM) method where frequency of the TWTA (traveling-wave-tube amplifier) is modulated every one second using a GPIB interface. When the speed of this switching increases, motion of the IPMC is expected to be more smooth.
5. IPMC rectenna

The IPMC rectenna is a stand-alone type of rectenna actuator; the rectenna pattern is fabricated on the electrode material of the IPMC. The rectenna can receive microwave signals and rectify to DC power; in addition, the IPMC rectenna can be used as a bending actuator by itself without any hard wiring to the power source. To test the feasibility of this integrated IPMC rectenna, the prototype is fabricated as shown in Figure 14.

Figure 15 shows sample images of the IPMC rectenna, taken by a digital microscope. Figure 15a shows diode integrated circuit (IC) pin silver soldering, and Figure 15b shows an edge of the IPMC rectenna fabricated by a milling machine. As shown in Figure 15, the connection of the pin and the surface of the IPMC electrode, and also the edge of
transmission lines, are acceptable; however, the measured voltage output radiated with 1W power (9 GHz) at 1 cm from a source antenna was under 100 mV.

To study the reason for the low voltage generated from the IPMC rectenna, performance simulation of a radio-frequency (RF) antenna was carried out using antenna analysis software [25]. The simulated antenna pattern had an 8.4 mm patch size and 50 Ω impedance. To compare the performance of the antenna, two electrode materials are simulated with the same dielectric constant substrate, Nafion® (Table 2). Figure 16 shows the result of far-field radiation patterns at the 9 GHz frequency with two electrode materials. With a copper electrode, the peak radiation is 6.46 dB; with a gold electrode, the peak is –37.6 dB. This shows that the radiation (perception) of the antenna with the gold electrode is unusable for the proposed IPMC rectenna design, due to poor conductivity. Figure 17 depicts the S11 (reflection coefficient) scattering matrix, which shows how much signal was reflected without being radiated (or perceived). As indicated in Figure 17, for the rectenna with the copper electrode, the antenna radiates (or perceives) with a -26dB return loss at 9 GHz; in contrast, with the gold electrode, radiation with a low return loss is observed as well as wide frequency range with an unusable specific frequency. From this simulation, it is
Table 2. The material specifications for the simulation.

| Property       | Copper electrode | Gold electrode |
|----------------|------------------|----------------|
| Dielectric constant | 4.0              | 4.0            |
| Thickness      | 0.25 mm          | 0.25 mm        |
| Conductivity   | 9,300,000        | 12,987         |

concluded that the conductivity of the electrode plays a key role in the performance of the proposed IPMC rectenna design. The electrical conductivity of copper is $63.01 \times 10^6$ S m$^{-1}$ and that of gold is $45.2 \times 10^6$ S m$^{-1}$.

Another reason for the low voltage could be due to its own RC characteristics of the IPMC. Figure 18 shows the RC equivalent circuit with a rectifier circuit. The RC equivalent circuit of the IPMC is composed of two resistors and a capacitor, whose electric characteristics are shown in Table 3. The IPMC under a microwave signal, the capacitor component of the IPMC acting as a short circuit, and the parallel combination of two resistors (R1 and R2), as shown in Figure 18, makes $130.23 \ \Omega$ valued single resistor. For the type of IPMC rectenna shown in Figure 14, a low-resistance value of the substrate (Nafion®) between the radiator and the ground degrades the performance of the patch antenna. However, for the RO3003® conventional microwave circuit material, the IPMC actuator for the rectenna shown in Figure 18b acts as a resistor load at a DC side; as a result, the microwave power can be transmitted to the IPMC actuator effectively. Further research must be done to pursue the applications for the IPMC rectennas, even if separate rectennas are not required to be attached to the IPMC actuator.

6. IPMC materials development and characterization: preliminary results

This study included preliminary development of an IPMC material potentially suitable for use in rectenna applications. As recently pointed by Tiwari and Garcia [26], types of the polymer layer (membranes in general) suitable for use in manufacturing IPMCs are diverse as long as they can have ionic exchange capabilities. For rectenna applications, we considered sulfonated dicarboxylic acid that could be more rigid and more functional at higher temperature than well-adopted Nafion. In order to investigate the thermal behavior and mechanical characteristics of a developed, sulfonated, fluorine-based polyamide [27], a differential scanning calorimeter (DSC, TA Instrument, USA) and dynamic mechanical analyzer (DMA, PerkinElmer, UK) were employed. The DSC test was scanned in a nitrogen environment with a $10^\circ$C/min scan rate. The DMA test was performed in a tensile mode as a function of frequency and temperature, using a 2 cm $\times$ 1 cm sample size. Standard electroless plating was implemented to manufacture the IPMCs, using platinum as an electrode metal. The electromechanical and electrochemical properties of the manufactured IPMCs were investigated using a potentiostat (Radiometer, Denmark) and a laser sensor (MicroEpsilon Optronic GmbH, Germany). The sample size was 5 cm $\times$ 1 cm. To investigate the microstructure of developed IPMCs, a scanning electron microscope (SEM) (Hitachi, Japan) was used.

Figure 19 shows the DSC test results of TFIPA-90 and Nafion® 1110. In this study, TFIPA-90 (0.9 equivalent of sulfonated dicarboxylic acid (2-sulfoterephthalic acid monosodium salt)) and Nafion® have different cations: Na$^+$ and H$^+$, respectively. The melting temperature, $T_m$, is evident in Nafion® at 250°C; however, due to its amorphous
Figure 16. Far-field radiation pattern of (a) a copper electrode and (b) a gold-coated electrode.
structure, no melting temperature is observed in TFIPA-90. It can be seen that Nafion® exhibits a semi-crystalline structure, and TFIPA-90 has a rigid polymer chain with an aromatic structure. Therefore, the glass transition temperature, $T_g$, of TFIPA-90 is slightly higher than that of Nafion®. From the DSC results, we can confirm that the TFIPA-90 membrane is more stable at a higher temperature than Nafion®. The decomposition temperature ($T_{de}$) was observed in both samples at 290°C, and corresponded to the loss of the sulfonated side group. The micrographs of the fabricated IPMCs are provided in Figure 20.

The mechanical properties of both Nafion® and TFIPA-90 were studied using DMA in a tension mode, as functions of frequency and temperature. The results are shown in Figures 21 and 22. For TFIPA-90, both the storage, as shown in Figure 21a, and the loss
Table 3. Electric characteristics of RC equivalent circuit of the IPMC.

| Component | Value   |
|-----------|---------|
| R1        | 160 Ω   |
| R2        | 700 Ω   |
| C1        | 1.0E-3 F|

modulus, shown in Figure 21b, were higher than those of Nafion® within the probed frequency range (0.01–100 Hz). The tan δ was lower in TFIPA-90 than in Nafion® due to the high storage modulus of TFIPA-90. The loss modulus of TFIPA-90 was high as well. As shown in Figure 22, the storage modulus of TFIPA-90 was significantly higher than that of Nafion® when the temperature was above the Tg. It is confirmed that the TFIPA-90, a rigid polymer, can be expected to be a mechanically stabilized membrane at high temperatures. Also, we have attempted to place platinum electrodes on TFIPA-90. But, the deposition of Pt was relatively poor compared to Nafion.

7. Conclusion and future work
In this research, a novel technology of transmitting power using the microwave and matching rectenna was realized in the laboratory experiment. The rectenna was composed of an antenna, an impedance matching circuit and a rectifying circuit. Electrical characteristics
Figure 19. DSC results of synthesized TFIPA-90 and Nafion®. The test was performed in a nitrogen environment with 10°C/min of scan rate [23].

Figure 20. Cross-sectional scanning electron micrographs of the micromorphology of a TFIPA-based IPMC [23].

of the rectenna were studied as well as the effect of frequency modulation of the microwave signals and the effect on the amplitude of the voltage generated from the rectenna. The rectifying circuit was designed to minimize the effect of a slow reverse motion of the IPMC actuator, due to poor dissipation of the charged IPMC during the forward motion. Also, a novel voltage doubler circuit was developed to transmit a higher voltage than the one that can be transmitted using a single diode rectifier.

The miniaturized 0.2 g rectenna could provide enough energy to drive the IPMC actuator. The concept of using frequency modulated microwave to actuate multiple IPMCs for different robotic applications was validated. It also was concluded that it is rather difficult to implement the self-contained form of an IPMC-rectenna design, due to a low transmissibility of the power to the actuator. The self-contained form of the actuator, in which the
Figure 21. DMA results of (a) a storage modulus, (b) a loss modulus, and (c) tan δ of synthesized TFIPA-90 and Nafion® as a function of frequency in the tensile mode [23].

Figure 22. DMA results (storage modulus, $E'$) of TFIPA-90 and Nafion® as scanned by temperature control in the tensile mode [23].
rectenna is embedded on the electrode surface of the IPMC, has the following challenges to be addressed in the future for actual implementation in robotics:

- A strong dependency of an electrode conductivity of the IPMC on the amplitude of voltages generated from the rectenna, and
- Inherent electrical characteristics of the IPMC that degrade the performance of the patch antenna.

In this work, based upon the properties of interest, the TFIPA-90-based IPMC is expected to be applied in the design of microwave-driven, robust robotic systems. Further research of its microstructure and micro pore characteristics may be required. Furthermore, with more material development there is an ample chance that we can improve the base polymeric material [28]. Once we have developed an optimized polymeric material and an effective process to put Pt on the surface, we will be able to perform full-scale testing.

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