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Pulse width-modulated signal for driving ionic electroactive polymer actuators

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*Abstract*— The ionic electromechanically active polymer (IEAP) actuators are perspective for use in miniature robots. To date, the development of robots using IEAP actuators is essentially in proof-of-concept level, only demonstrating the principle of locomotion. The choice of the most appropriate input signal for driving these actuators has found only little interest. However, novel types of IEAP actuators have been developed in the recent years. The state-of-the-art IEAP actuators provide actuation amplitude and force already at such levels that real-world robots are to emerge. Here, we explore the possibility of using simple PWM-based input signal for driving the IEAP actuators.

# INTRODUCTION

Ionic electromechanically active polymer (IEAP) actuators have been considered as promising materials for biomimetic robotic applications since the beginning of their development.[1] The IEAP-based microrobots are light in weight, soft, compliant, and noise-free.[2, 3] Therefore, they find potential use in rescue work in disaster zones, civil or military surveillance, aerospace engineering,[4] or in space missions[5]. In comparison with other smart electrically actuated materials, the IEAPs have considerable advantages. The IEAP actuators are characterized by low elastic modulus, large deflections, and a large force-to-weight ratio. More importantly, the working voltage of the IEAPs is only in the order of a few volts.

To date, many proof-of concept level microrobots have been developed by various research groups. For example, of IPMC-driven underwater robots, inspired by, for example, rays[6], jellyfish,[7] stalked protozoa,[8] insects,[9] or snakes[10], have been proposed. The IEAP actuators on such visionary robots are, to date, driven by rectangular or sinusoidal input voltage, or less often by constant current. In real-world microrobots, the successful driving electronics must be the simplest in construction, the cheapest in prize, the smallest in dimensions, and lightest in weight.

The generation of analog output voltage of a certain level is considerably difficult using cheap and widely available microcontrollers, as external digital-analog converters and current-amplification blocks are required. At this point, the advantages of pulse width-modulated (PWM) driving signals are revealed. The state-of-the-art cheap and widely available microcontrollers are, as a rule, equipped with PWM output channels. The timing for these PWM channels is implemented using hardware timers rather than in software. The PWM signals are especially advantageous for driving devices with mechanical inertia such as electric motors, but find use also in a variety of other uses where control of electric current is desired.

In the design of autonomous robots, energy efficiency is an important concern. The PWM control is advantageous also from this point of view, as only switching action for the input signal is required. Generally, the high-current analog signal amplifiers tend to be less efficient than the PWM-based controllers.

In the field of IEAPs, PWM control has been previously applied by Shoji et al. on the IPMC actuators to achieve a better control over the force and displacement.[11] Shoji, however, used a PWM control signal which is substantially different from the signal used in this work. In Shoji’s work, the control voltage alternates between the maximum voltage (2 V) and the short-circuit condition in every working cycle. By doing so, the IPMC is both charged and discharged during each PWM period. The total accumulated charge is related to the PWM duty cycle, but the power losses increase with the decrease in the duty cycle. Obviously, such a driving signal wastes energy and is therefore not suitable for use in autonomous devices. Moreover, in the Shoji’s work, the PWM is applied at frequencies as low as it causes the actuator to respond by vibrating along (2…100 Hz), which is unnecessary and does not convey the essence of the PWM signal – current control.

The IEAP actuators are characterized by low input voltages – in the order of 0.1…5 V. One reason why PWM signal is rarely considered for driving IEAPs is the conception that the input signal should be as low as possible. It is known that the actuation amplitude of the IEAP actuators is dependent on its charging level.[12] The charging level is in turn proportional to the open-circuit potential on the IEAP electrodes. It is clearly demonstrated in this work that the open-circuit potential on the IEAP electrodes and the level of input voltage can be drastically different. Therefore, input voltages much higher in amplitude than the maximum permitted open-circuit potential on the IEAP can be used.

In this work, we constructed a PWM-based driving circuit for powering an IEAP actuator. The performance and energetic efficiency between PWM and sinusoidal input is compared.

# Experimental

## Actuator

An IEAP actuator with carbide-derived carbon electrodes and gold current collectors was used for testing the driving signals. The actuator was used in a cantilever configuration – the input signal was applied from its rigidly clamped end.

## PWM generation

PWM input signal was generated with a custom-made electronic circuit, which mimics the potential real-world application. The experimental set-up is depicted in Figure 1. The circuit is based on an *Atmel* ATTINY13A microcontroller. The microcontroller has two dedicated PWM outputs. These outputs can be connected to either positive or negative terminal of the power supply, or switched between these two voltages using PWM. The output current was amplified using a DRV8837 H-bridge driver IC. The outputs of the driver are connected to either positive or negative terminal of the power supply, depending on the signal level in its input ports. The used H-bridge can be also switched having high-impedance output on both of the output channels.



1. The experiment set-up for PWM driving of the IEAPs.

The test circuit was powered using a custom-made power supply based on OPA548 operational amplifier. The amplifier was equipped also with a current-measurement circuitry. The total current consumption of the system consisting of all of the driving electronics and the IEAP was measured. The current consumption of the IEAP was calculated by straightforwardly subtracting the current consumption of the system with the IEAP disconnected.

## Sinusoidal input

Sinusoidal input signal was used as a reference. The microprocessor and H-bridge were removed from the circuit. Sinusoidal input voltage at appropriate amplitude was generated using the same OPA548-based signal generator. The outputs of the signal generator were directly connected to the IEAP terminals.

## Electrical and electromechanical measurements

The terminal voltage on the IEAP was measured using a *National Instruments’* PCI-6036E DAQ device.

The blocking force was measured by attaching a MLT0202 isometric force transducer by *ADInstruments* to the opposite end of the clamped actuator.

The free-bending curvature was determined using image analysis. The actuation was filmed using a *DMK 22BUC03* USB camera and the curvature was extracted using image recognition modules in the *National Instruments’ Labview* programming environment.

# Results

## Performance of the IEAP driven by PWM signal

IEAP was driven using a bipolar PWM signal of a constant period and frequency. In the timeframe of 10 s, the PWM signal resulted in galvanostatic charging of the IEAP. The duty cycle of the PWM signal determines the charging current averaged in time and therefore the amount of charge injected to the IEAP in one charging cycle. Figure 2 show that the IEAP charging current dropped only 20% during a 10-s charging cycle.



1. The current consumption in case of PWM input.

Figure 3 gives a typical course of voltage on the IEAP terminals during one working cycle. In the first half of one working cycle, the IEAP was first charged having one polarity, and then it was short-circuited. Subsequently, the polarity of the input voltage was reversed and the IEAP was charged having the opposite polarity. The voltage on the IEAP terminals is switched between power supply voltage and the IEAP open-circuit voltage at 32 kHz – that is, the PWM frequency.



1. A representative course for IEAP terminal voltage in case of PWM driving signal.

## Efficiency

The highest open-circuit voltage, which is in turn related to the level of charging, increases in proportion to the PWM duty cycle, as depicted in Figure 4. The amount of charge required in each cycle, instead, increases exponentially with the increase in PWM duty cycle. The driving electronics itself consumes current at a constant level of 3.8 mA. The relation between the amount of charge needed by the electronics and the IEAP is illustrated in Figure 4 – at 23.5% duty cycle, 10 % of the charge is consumed by the driving electronics. Nevertheless, the duty cycle of 12% provides the most force per consumed charge, as shown in Figure 5.



1. The consumed electric charge and the peak open-circuit voltage on the IEAP at different PWM duty cycles.

In-between the consecutive charging cycles the actuator was short-circuited by applying the same voltage to both of the electrodes, as illustrated in Figure 4a. In particular, both of the electrodes were connected to the negative terminal of the power supply. (In the case of using the same H-bridge to drive DC motors, this regime restrains the DC motor from turning.) It is important that by using an H-bridge for short-circuiting, no additional current was drawn from the battery, as shown in Figure 2. For a comparison, when the IEAP is driven with a sinusoidal or rectangular input voltage, the energy stored in the battery is consumed for both charging and discharging of the IEAP. The use of a 3-s short-circuiting cycle between the working cycles provided up to 15% higher force and 10% more force per charge, as given in Figure 5.



1. Energy saving by short-circuiting.

## Comparison between PWM and sinusoidal driving signal

It is remarkable that neither the performance nor cycling stability of the IEAP actuator suffered as a result of a pulsed control signal with the voltage on its terminals alternating between 0 and 4 V at 32 kHz.



1. The blocking force in relation to the consumed charge per cycle for pulse width-modulated and sinusoidal input signals. The power consumption of the driving electronics has been subtracted in case of modulated signal.

Figure 6 demonstrates that virtually the same amount of charge is consumed both in the case of sinusoidal and PWM driving signals of equivalent cycling frequency to achieve the same bending curvature amplitude. The maximum blocking force shows a small (15%) decrease compared to sinusoidal input of the same frequency, as depicted on Figure 7. The blocking force is, however, sensitive to the cycling frequency - Figure 7 shows that the blocking force decreases 30% at twice lower cycling frequency.



1. The free-bending curvature in relation to the consumed charge per cycle for pulse width-modulated and sinusoidal input signals.

# Conclusion

Microrobotics is a perspective application for the IEAP actuators. For successful development of any mechatronic device, the choice of control signal is of great importance.

 PWM signal has proved to be efficient for driving the IEAP actuators. The performance of the actuator did not suffer from the use of control waveform that alternates at frequency as high as 32 kHz. The coulonometric measurements showed that the PWM signal gives the same amount of deflection for the amount of consumed charge.

It is known that an electromagnetic motor can be restricted from turning by short-circuiting its terminals. Doing so, the inductive current counteracts the rotation. It is shown that the same analogy is well applicable also for IEAP actuators. By actuating an IEAP actuator, charge is injected and stored into the IEAP. It holds its position when open-circuited. To date, the actuator has been driven to the opposite direction only by applying current with the opposite polarity. However, it is shown that short-circuiting of the actuator can save a significant amount of energy and is therefore if great interest in development of autonomous devices.

PWM-based control boards are cheap, simple, and widely available. The working voltage of the IEAP is in the same range with state-of-the-art microelectronics – a few volts. Therefore, the integration of IEAP actuators or sensors into miniature mechatronic systems is straightforward. Therefore, a pathway towards use of the IEAPs in the real-world applications such as microrobotics is widened.

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