Power Optimization in Battery-Powered Micro-Motors

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Abstract

Recent advances in integrated circuits and micromachining have enabled the integration of battery-powered micro-actuators in miniaturized drug delivery systems. However, the power/energy management system that treats current overloading remains sub-optimal. Overloading not only deteriorates the actuators' long-term performance but also attenuates battery capacity. In this work, we are proposing a simple yet powerful solution to manage current overloading to maximize battery-powered system life-time. The proposed solution consists of a digitally programmable soft starter and DC-DC converter that can dynamically balance the trade-off between inrush current amplitude and motor starting speed as well as maximally minimize the continuous current draw from a battery. Our experimental results show that the proposed soft starter alone can enhance the battery capacity by 18% and together with the DC-DC converter, they can increase the drug delivery cycles by 33% without sacrificing the system's output performance.

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I. INTRODUCTION

Automated drug delivery systems are revolutionizing the way that drugs are administrated for long-term care [1], [2] and emergency medicine [3], [4]. On-demand, pulsatile, and long-term continuous drug delivery can all be easily implemented by an electrical pump system [5]. It is also the key component for constructing a closed-loop drug delivery system [6], [7]. Such automated delivery systems typically consist of a battery, power management circuit, actuator driver circuit, and actuator. In the past two decades, biomedical engineering researchers have primarily focused on developing various kinds of novel actuators while ignoring the importance of power management and driver optimization when powered by a battery with limited capacity [8].

Current overloading is the most common power management issue in electrically powered devices, requiring well-tailored power supply systems [9], [10]. Unlimited current overloading not only deteriorates the actuator's durability but also attenuates battery capacity, thus shortening the system's lifetime [10].

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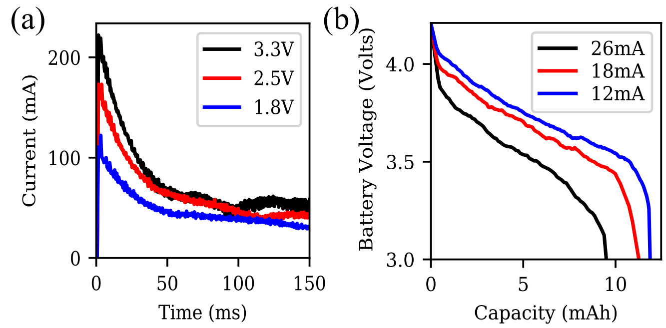

Fig. 1. (a) Inrush current of a motorized system with varying driving voltages, (b) battery discharging characteristics with varying continuous current (CC) draw of which the maximum rated continuous discharging current is equal to 30 mA, and the rated capacity is 15 mAh.

Inrush current, which is the maximum instantaneous input current drawn by an electrical device when first turned on, is one of the major types of overloading conditions. Its amplitude is proportional to the driving voltage and is typically five to ten times higher than the steady-state current, as shown in Fig. 1(a). Although existing solutions have successfully solved this issue by means of a current limiter to inhibit current overloading [9] or a soft start methods [11], they suffer in either generating extra continuous current consumption or slowing the system starting speed. Moreover, these solutions are not digitally programmable, which inevitably compromise the system flexibility [12], [13].

In addition to inrush current, continuous high current consumption from a motor places another major burden to a battery. When determining maximum continuous current supply provided by a battery, it often relies on the battery datasheet to ensure no permanent damage to the battery. However, simply setting the current draw lower than the maximum rating does not guarantee preservation of the battery's condition. Fig. 1(b) shows battery discharge characteristics subjected to various discharging current levels. Although the discharging currents are below the maximum rating, they all show different degrees of attenuation in the capacity. The higher the current draw is, the faster the voltage drops, and the more the capacity is attenuated.

In this work, we propose a digitally programmable circuitry to mitigate the battery attenuation due to the inrush current and the continuous current consumption of a motor. The first part of this work shows that the proposed digitally programmable soft start method can effectively balance the trade-off between inrush current and the starting speed. The second part of the work shows how the programmable

DC-DC converter is able to not only reduce the energy consumption of a motor but also minimize the current draw from the battery, which results in increasing the total number of drug delivery cycles. This work also reveals that the optimization of battery lifetime should not only consider the power/energy consumption of actuators but also the overall circuit conversion efficiency and battery discharge characteristics.

II. Materials and Methods

An automated drug delivery system mainly consists of a battery, power management circuit, actuator, actuator driver, and drug reservoir. This work primarily focuses on the optimization of its power management circuit and actuator driver to maximally sustain the battery capacity and actuators' long-term performance.

A pin-type lithium-ion battery (CG-320A) with a rated capacity of 15 mAh, the maximum continuous current draw of 30 mA, and the nominal voltage of 3.8 V is employed as the power source. A sub-micro plastic planetary gear motor with gear ratios of 26:1 from Pololu is used for the investigation of inrush current and power optimization. A DC-DC converter (TPS63060) with programmable output voltage is employed. A digital 200 kΩ potentiometer (DP, MAX5419) with 256 steps using I^2C interface is used to dynamically adjust the DC-DC converter output voltage. An N-type MOSFET with a low dropout voltage (0.15 V) is used to regulate the motor driving voltage. A digital to analog (DAC, MCP4725) with I^2C interface is employed to control the MOSFET. A microcontroller unit (MCU, nRF52840) is employed to control the DP and DAC. A power profiler kit (PPK) II from Nordic was used to capture and characterize the battery's transient and continuous current draw.

A. System Architecture

The power management circuit and the actuator driver are integrated to enable power optimization in both the actuator and battery. The battery is connected to a low-dropout linear regulator (LDO) with dual output voltage to provide the MCU with a 1.8 V logic level and the DAC and DP with a 3.3 V logic level as shown in Fig. 2. In addition, the battery is also connected to the DC-DC converter to power the actuator. The output voltage of the DC-DC converter can be dynamically regulated by the DP with the voltage range between 0.7 V and V_{BAT}. The driving voltage of the actuator is further regulated by the N-type MOSFET whose gate-source voltage is controlled by the DAC to enable faster dynamic responses during the soft start.

B. Soft Start Strategies

Using a current limiter is the most intuitive way to limit current overloading. Here, we utilized the current limiting function from a DC power supply (RIGOL DP831) to characterize its performance in mitigating the inrush current.

To date, soft start methods have been shown to be the most effective approach in mitigating inrush current by gradually ramping up the actuator driving voltage, which

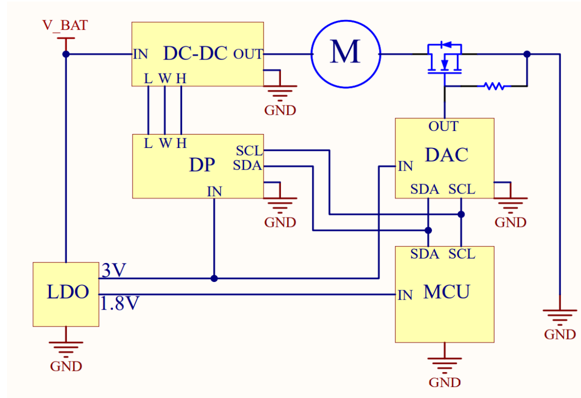

Fig. 2. Circuit schematic of the power management system

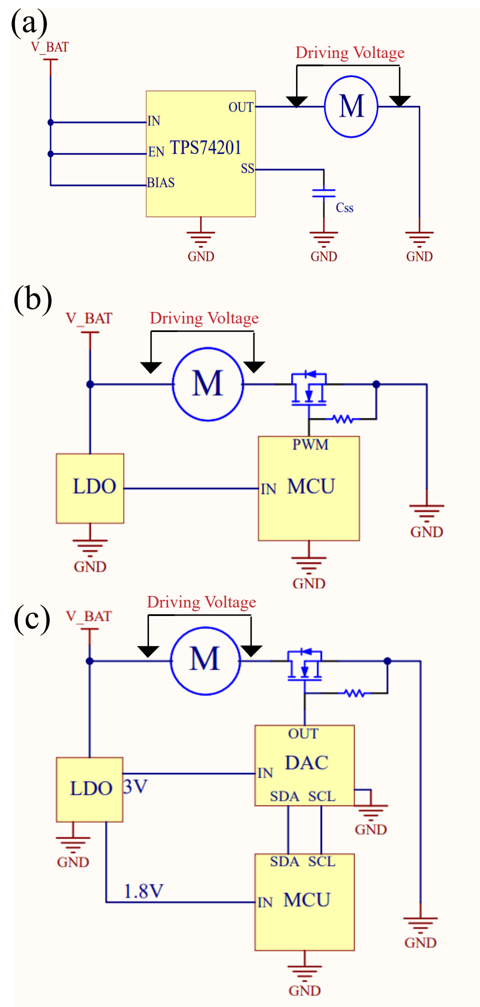

Fig. 3. Circuit schematics for various soft start strategies : (a) Circuit-based (using Capacitor), (b) PWM-based, (c) DAC-based

typically results in slowly reaching maximum speed. We have comprehensively evaluated various soft start strategies and discussed their pros and cons.

1) Circuit-based soft start: A programmable soft starter (TPS74201), which is also a kind of LDO, was tested. The soft start ramp-up time is set by an external capacitor, which is determined by

$$t_{ss} = \frac{V_{REF} \times C_{ss}}{I_{ss}} \tag{1}$$

where V_{REF} is the reference voltage (which equals 0.8V), C_{ss} is the soft start capacitor, and I_{ss} is the charging current (which equals 0.73 μA). The circuit schematic is shown in Fig. 3(a).

2) PWM-based soft start: Pulse-width modulation (PWM) is an easy and common way to adjust driving voltages by means of quickly switching a voltage source on/off with a varying duty cycle. The PWM frequency is 400 Hz and generated from one of the MCU's digital pins with 8-bit resolution and a logic level of 3.3 V. The digital pin connects to the gate of the MOSFET as shown in Fig. 3(b). The PWM-controlled gate-source voltage (V_{GS}) results in PWM-modulated drain-source voltage (V_{DS}).

3) DAC-driven soft start: A DAC was employed as an alternative to the PWM solution, enabling a non-linear driving voltage (Fig. 3(c)). Soft start signals generated from the DAC would be fed into the MOSFET as V_{GS} to modulate V_{DS}. A MOSFET has three different operating regions: ohmic mode, linear mode, and saturation mode. The linear mode operation is the only way that V_{DS} can be modulated by varying the V_{GS} in which the DAC voltage is between the V_{GS} threshold, V_{GSth} (2.2 V) and the saturation voltage (2.45 V). To benchmark the non-linear soft start control signals, $V_{GS} = t^{0.1} + V_{GSth}$, $V_{GS} = t^{0.4} + V_{GSth}$, $V_{GS} = t + V_{GSth}$, $V_{GS} = t^{1.5} + V_{GSth}$ were generated from the DAC and fed into the MOSFET as V_{GS}.

C. Programmable DC-DC converter

A dynamically programmable DC-DC converter was employed to convert the battery voltage (V_{BAT}) to the actuator's driving voltage. The output voltage of the DC-DC converter can be adjusted by a digital potentiometer with the voltage range from 0 V to 3.6 V, which is described as

$$V_{out} = 0.5 \cdot (1 + \frac{R_1}{R_2}) \tag{2}$$

where $\frac{R_1}{R_2}$ is the resistance ratio controlled by the digital potentiometer. The relationship of power between the input and output of the DC-DC converter can be expressed as:

$$I_{BAT} = (\frac{\varepsilon \cdot V_{out}}{V_{BAT}}) I_{out} \tag{3}$$

where ε is the conversion efficiency of the DC-DC converter and V_{BAT} is the battery voltage. As V_{out} is set to always be lower than V_{BAT}, the converter could ensure the current drawn from the battery is lower than the current draw from the motor.

III. Results and Discussion

A. Inrush Current Mitigation

The simplest way to mitigate current overloading is using a current limiter which only consists of passive electronic components. It is also known that current limiters are energy inefficient solutions. However, the dynamic response in do soft start has not been fully elucidated. Fig. 4 shows the result of current draw and voltage applied on the actuator with a current limiter that limits the maximum current to 50 mA. Considering the unavoidable voltage drop-off of 150 mV from the MOSFET, the actual driving voltage applied to the actuator would be 3.15 V. It is clear that the inrush current was completely removed. However, the driving voltage was self-regulated by the current limiter and took more than 10 s to reach 3.15 V.

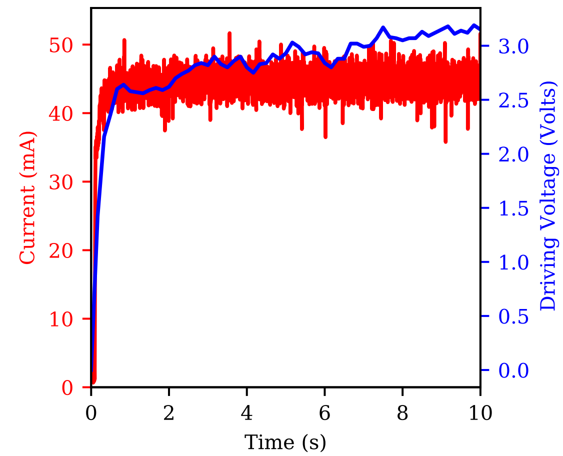

Fig. 4. Current response and driving voltage of the actuator by means of a current limiter

1) Circuit-based solution: Instead of directly limiting current, a circuit-based soft starter that does not consume extra energy by gradually ramping up the driving voltage in a linear manner could be an ideal alternative. The circuit utilizes the capacitor's linear charging characteristics to determine the soft start speed. Higher capacitance requires a longer charging time, thus resulting in a longer soft start period as shown in Fig. 5(a). The corresponding circuit diagram is shown in Fig. 3(b). The soft start with the capacitance of 81 nf required a charging time of about 100 ms and resulted in the inrush current amplitude of 83 mA (Fig. 5(b)). By increasing the capacitance from 81 nf to 470 nf, it required a longer charging period of about 400 ms. In doing so, the inrush current was reduced to 60 mA. It is also shown that a prolonged soft start period with a capacitance of 1160 nf can completely eliminate the inrush current. However, this approach sacrifices the time to reach its maximum speed. Here, it took about 1 s to reach steady-state current (Fig. 5(b)). We, therefore, observe a strong trade-off between inrush current and soft start speed. A major drawback of this approach is that the soft start period is not dynamically adjustable. Changing the soft start speed requires changing the capacitance on the circuit. A variable capacitor is usually not a solution here due to the wide range of capacitances and the form factor of the component.

2) PWM-based solution: PWM has been employed as a more flexible soft start solution, which allows for the

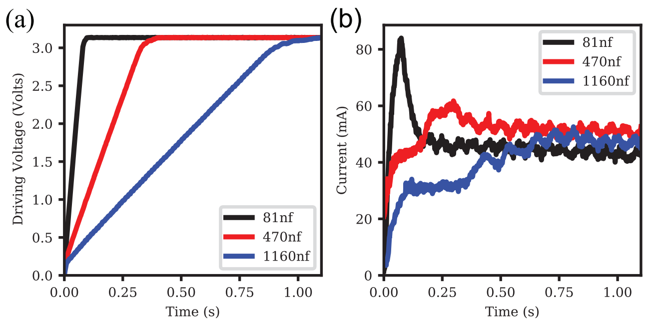

Fig. 5. (a) Driving voltage trends of a motorized actuator using circuit-based soft start with varying capacitance. (b) Current responses of a motorized actuator using circuit-based soft start with varying capacitance

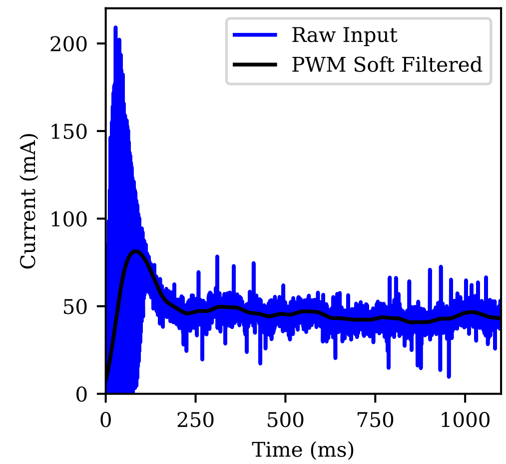

Fig. 6. Current response of a motorized actuator using PWM-based soft start

dynamic adjustment of soft start signals. The driving voltage can be dynamically adjusted by MCU generated PWM signals (Fig. 3(b)). Fig. 6 shows the current response of the actuator by means of the PWM-based soft start method. The "PWM Soft Filtered" shows that the inrush current can be visually reduced after a digital low pass filter with a cut-off frequency of 400 Hz. However, the "Raw Input" meaning the data without digitally filtering, shows the actual inrush current is even higher than that without implementing a soft starter. The inrush current from the "Raw Input" curve is induced by the PWM signal that quickly switches the MOSFET on/off. To effectively eliminate the PWM-induced noise, it requires a bulky RC circuit that usually occupies a large footprint and is not a feasible solution for a small-scale mechatronic system. Furthermore, the high frequency and amplitude pulses create a high risk of damaging motor brushes.

3) DAC-based non-linear solution: Up until now, we have evaluated different kinds of solutions for mitigating the inrush current and discussed their pros and cons. Learning from the major drawbacks of the current limiter with slow dynamical response capability, the circuit-based soft starter with a fixed soft start speed, and the PWM-based soft starter with high frequency noises, we are proposing a DAC-based solution to enable dynamically adjustable soft starter (Fig. 3(c)). Fig. 7 shows the current responses induced by various non-linear driving voltages. Fig. 7(a) shows that the inrush current can be reduced to less than 80 mA by quickly increasing the driving voltage to 3V within a period of 5 ms and slowly reaching 3.15 V in another 40 ms. By prolonging the soft start period to 300 ms, the inrush current can be reduced to 50 mA, which is similar to the results in Fig. 5. Increasing the soft start period further does not result in an obvious reduction of inrush current but does significantly slow system response. Fig. 7 (c) shows how the DAC-based solution can perform a linear soft start to replicate the result produced by the circuit-based solution with the capacitance of 470 nf. All the non-linear control signals can easily be generated from a microcontroller with DAC.

To investigate how inrush current and the effect of soft start contribute to battery attenuation, we designed an experiment to repeatedly operate the actuator with 50% duty cycle and a turn-on period of 250 ms. The results are shown in Fig. 8. The system without soft start under frequent inrush currents with amplitudes of 140 mA resulted in a fast drop in the battery voltage and 25% reduction in the battery capacity. We also observe that the soft start approach can reduce the inrush current to 50 mA and achieve less than 10% reduction in the battery capacity.

B. Reducing Burdens in Continuous Current Draw

Beside the inrush current, high continuous current would cause larger attenuation in the battery capacity. The current consumption of the DC motor is proportional to its driving voltage. To effectively and dynamically modulate the driving voltage, we adopted a programmable DC-DC converter whose output voltage is controlled by DP (Fig. 2). The current draw of the motor and speed of the motor with varying driving voltage are characterized in Fig. 9(a). The motor speed and current draw are linearly proportional to the driving voltage. Intuitively, higher speed requires higher power consumption. However, the required energy for a DC-motor-based drug delivery device to deliver a fixed amount of drug with varying speeds remains unclear. Fig. 9(b) shows the energy delivered from the battery and the energy consumption of the motor to deliver 500μL drug at various driving voltages. The difference in energy between the battery and motor is the unavoidable energy conversion loss from a DC-DC converter. Ideally, the energy consumption of the motor should be identical to the energy delivered from the battery when the conversion efficiency of the DC-DC converter is 100%. It is shown that reducing the voltage from 3.3 V to 1.5 V results in lower energy consumption from both the battery and motor sides. Repeatedly reducing the driving voltage results in discrepancies between the battery and the motor, which is caused by the dramatic drop in the conversion efficiency (ε) at lower output voltages. This issue can be addressed in the future by employing a DC-DC converter with higher conversion efficiency at low output voltages. From the battery side, the energy consumption

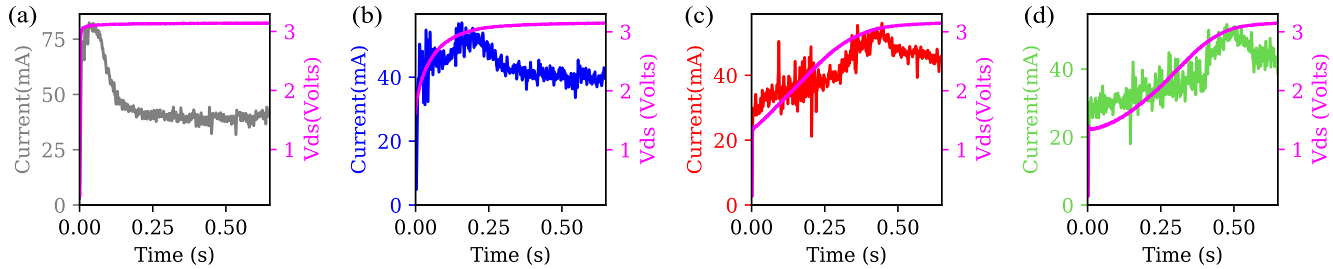

Fig. 7. Current responses of a motorized actuator using DAC-based soft start for different non-linear control signals : (a) $V_{GS} = t^{0.1} + V_{GSth}$, (b) $V_{GS} = t^{0.4} + V_{GSth}$, (c) $V_{GS} = t + V_{GSth}$, (d) $V_{GS} = t^{1.5} + V_{GSth}$

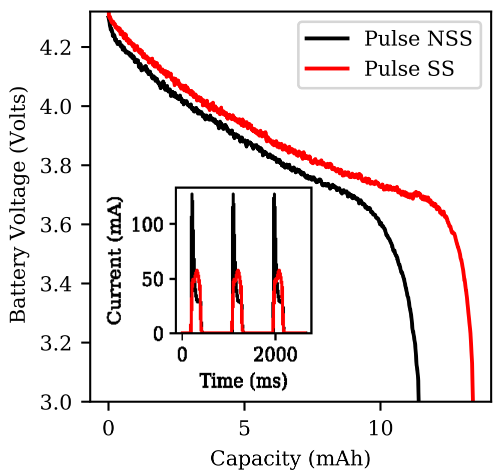

Fig. 8. Battery capacity attenuation by inrush current and mitigated inrush current

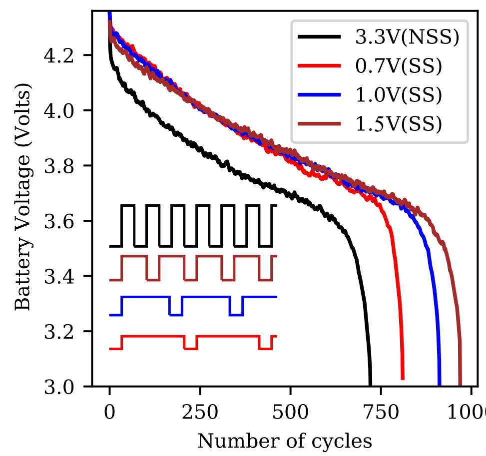

Fig. 10. Number of drug delivery cycles with various steady state driving voltages

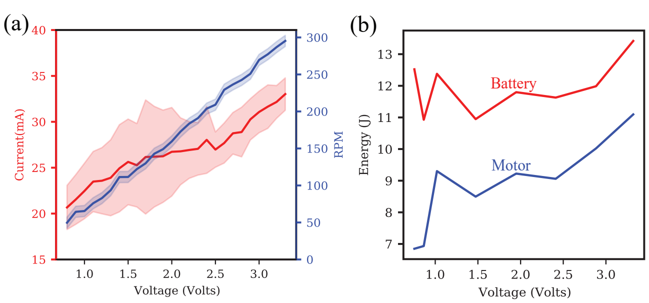

Fig. 9. (a) RPM and current trends of a motorized actuator with varying voltages, (b) Energy consumption by a motorized actuator from the battery and motor side with varying voltages

increases when the voltage is reduced from 1.5 V to 0.75 V. From the motor side, the energy consumption gets lower when decreasing the voltage from 1.5 V to 0.75 V. Table I shows the input and output power as well as the conversion efficiency of the DC-DC converter with varying the output voltage.

From the results of energy consumption in Fig. 9 and power conversion in table I, we know that the lowest energy consumption happens at a driving voltage of 1.5 V and the lowest current draw from battery happens at a driving voltage of 0.75 V. However, it is not clear which driving voltage should be chosen to achieve the maximum number of drug delivery cycles. To evaluate the long-term performance of the DC-motor-based drug delivery system at various driving voltages, we conducted experiments which ran the motor repeatedly to deliver 500 μL drug at 3.3 V without doing soft start, 1.5 V with soft start, 1.0 V with soft start, and 0.7 V with soft start all with 1 s off every time after completing the delivery. It is not surprising that 3.3 V without soft start resulted in the lowest total number of delivery cycles and also a faster battery voltage drop. While it is surprising to us that the driving voltage of 0.7 V ran much less cycles than that of 1.0 V and 1.5 V as it consumed almost the same energy from the battery as that of 1.0 V (see Fig. 9) and drew about 23% and 50% less current than that of 1.0 V and 1.5 V respectively (see table I). Eventually, the driving voltage of 1.5 V resulted in the highest number of drug delivery cycles, which could be a balanced result between the current draw from the battery, energy consumption, and the time taken to complete the drug delivery. It is worth mentioning that the drug delivery speed at 1.5 V is only half of that at 3.3 V, but the overall battery lifetime at 1.5 V is 33% more than that at 3.3 V.

As a brief summary of the DC power optimization, it is essential to consider all the perspectives in energy consumption, circuit conversion efficiency, battery capacity

TABLE I
POWER CONVERSION EFFICIENCY OF THE DC-DC CONVERTER

V_{in} (Volts)	V_{out} (Volts)	I_{in} (mA)	I_{out} (mA)	P_{in} (mW)	P_{out} (mW)	ε (%)
3.7	3.32	35.7	32.9	132	109	82.69
3.7	2.88	26.19	28.09	96	81	83.6
3.7	2.42	21.35	25.52	79	61	77.91
3.7	1.95	15.84	23.52	58	46	78.18
3.7	1.47	10.98	21.4	41	32	76.1
3.7	1.02	7.3	19.9	27	20	75.14
3.7	0.86	6.34	17.2	23.4	15	63.46
3.7	0.75	5.6	15	20	11	54.69

attenuation, and the operating time in the continuous current draw to maximize the system lifetime.

IV. Conclusion

This work proposed a simple solution for battery-powered microactuators to manage different kinds of current overloading conditions that might attenuate the battery performance or deteriorate the actuators' durability. To balance the trade-off between the inrush current and starting speed, we proposed a digitally programmable soft starter to effectively mitigate the current overloading without sacrificing its dynamic output performance. In addition, we proposed a programmable DC-DC converter that can significantly minimize the continuous current draw from a battery to avoid the attenuation in battery capacity. Finally, we revealed that it is necessary to consider not only the energy consumption of the motor but also the circuit performance and battery capacity attenuation.

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