Supplementary Information for

DropBot: an open-source digital microfluidic control system with precise control of electrostatic driving force and instantaneous drop velocity measurement

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Methods and materials

Reagents and materials

Unless otherwise specified, general-use reagents were purchased from Sigma Chemical (Oakville, ON, Canada) or Fisher Scientific Canada (Ottawa, ON, Canada). Deionized (DI) water had a resistivity of ~18 MΩ•cm at 25°C.

DMF device fabrication

DMF devices were fabricated in the University of Toronto Emerging Communications Technology Institute (ECTI) cleanroom facility using a transparent photomask printed at 20,000 DPI (Pacific Arts and Designs Inc., Markham, Ontario). Bottom-plates bearing chromium electrodes were patterned by photolithography and etching of commercially available chromium and positive photoresist-coated, 50×75 mm glass slides (Telic, Valencia, CA). Substrates were exposed to UV through a mask (8 s, 29.8 mW/cm^2), developed in MF-321 (~2 min), and etched in CR-4 (5 min, OM Group, Cleveland, Ohio), followed by washing with DI water and drying under a stream of nitrogen. Substrates were then immersed in AZ 300T for 10 min to remove the photoresist, and again washed in DI water and dried with nitrogen. Silanization solution was prepared by mixing 2 mL 3-(Trimethoxysilyl)propyl methacrylate (Specialty Coating Systems, Indianapolis, IN), 200 mL DI water, 200 mL isopropyl alcohol (IPA), and 1 mL acetic acid (BioShop, Burlington, ON, Canada) for 2 hours at room temperature. Substrates were immersed in this silanization solution for 10 min, rinsed with IPA and cured at 80°C for 10 min, followed by rinsing with IPA and drying with nitrogen. Slides were then coated with Parylene-C by evaporating either 5 g (for most devices) or 15 g (for a few devices) of Parylene dimer in a vapor deposition instrument (Specialty Coating Systems, Indianapolis, IN). Profilometry revealed these thicknesses to be 2.2 and 6.2 μm, respectively. Substrates were then coated with ~50 nm of Teflon-AF 1600 (DuPont, Wilmington, DE) by spin-coating (1% wt/wt in Fluorinert FC-40, 1000 rpm, 30 s) and postbaking at 160°C for 10 min.

50×75 mm Indium tin oxide (ITO)-coated glass substrates (Delta Technologies Ltd., Stillwater, MN) were coated with Teflon-AF (50 nm, as above) for use as top-plate substrates. All experiments were carried out on devices bearing a rectangular array of 15×4 square actuation electrodes (2.2×2.2 mm each), 8 reservoir electrodes (6.5×15 mm each), and inter-electrode gaps of 25-75 μm. Each electrode is connected to a contact pad on the sides of the device and contact pads are arranged in 6 columns of 15 rows (3 columns per side). The contact pads are spaced every 2.54 mm, and are designed to interface with a custom pogo-pin connector. Devices were assembled such that the ITO top plate was roughly aligned with the outer edges of the reservoir electrodes on the bottom plate. The two plates were separated by a spacer formed from two pieces of double-sided tape with a total thickness of ∼150 μm, resulting in drops of ~0.8-1.0 μL covering a single actuation electrode.

DropBot hardware and software

The source code and circuit schematics are available at http://microfluidics.utoronto.ca/dropbot. An overview of the system components is shown in Figure 1 in the main text. The graphical user interface is written in Python (http://www.python.org) using the GTK toolkit (http://www.pygtk.org). The control board relies on an Arduino Mega 2560 (SmartProjects, Italy) and connects to a computer via USB. The control board houses a custom circuit for measuring the amount of current passing though the device and through a reference resistor to infer device impedance and amplifier output, respectively. A simplified version of this circuit is shown in Figure 2a in the main text; the design builds on earlier versions,[1–3] with the notable addition of a switchable bank of resistors (with resistances of 1 kΩ, 10 kΩ, 100 kΩ and 1 MΩ) to extend the dynamic range by several orders of magnitude and an extra channel for measuring the amplifier output in addition to device impedance.

The control board generates a 0-1.4 V_{rms} variable-frequency sine wave using an LTC6904 oscillator (Linear Technology, Milpitas, CA) and low-pass filter. This signal is amplified by a PZ700 amplifier (Trek, Inc., Medina, New York) and is connected to the input of three custom-built high-voltage driver boards, each housing 40 solid-state relay switches; this gives the system a total of 120 channels. The amplifier output is also connected through a 10 MΩ resistor back to the control board to facilitate amplifier-output monitoring. The control board communicates with the driver boards over an i2c bus (NXP Semiconductors, Eindhoven, Netherlands), and each relay switch connects to a single electrode on the DMF device via a custom pogo-pin connector.

Calibration for parasitic capacitance

Figure 2a in the main text shows the circuit model for the impedance and amplifier monitoring circuit. The capacitors (red) represent the combined parasitic capacitance of the coax cables, circuit board traces, connectors, etc. Amplifier output, V_{total}, was measured using a TDS2021 oscilloscope (Tektronix, Beaverton, OR). The attenuated amplifier voltage, V_{hv}, was measured by the Arduino for 30 frequencies evenly spaced between 0.1 and 30 kHz on a $\log_{10}$ scale. The input signal was adjusted such that V_{hv} was within the measurable range for the Arduino (0-5 V). The parameters R_{hvi} and C_{hvi} (i=0, 1) were estimated using the Levenberg–Marquardt algorithm for nonlinear least-squares[4] by fitting Equation 2. The R_{fbj} and C_{fbj} (j=0, 1, 2, 3) terms were estimated similarly by attaching load resistors of 1 or 10 MΩ in place of the device. Using these calibration values, the device impedance was estimated using Equation 3:

$$\boldsymbol{Z_{device}(f)} = \frac{\boldsymbol{R_{fbj}}}{\sqrt{\boldsymbol{1+\left(2\pi R_{hvj} C_{hvj} f\right)^2}}}\left(\frac{\boldsymbol{V_{total}}}{\boldsymbol{V_{fb}}} - \boldsymbol{1}\right) \quad (3)$$

where $Z_{device}(f)$ is the device impedance in Ohms as a function of frequency, V_{fb} is the voltage measured by the control board across resistor R_{fbj}, and C_{fbj} is the parasitic capacitance when feedback-resistor j is selected.

Velocity experiments

Drops of DI water were translated across a set of four electrodes using a driving frequency of 10 kHz and voltages starting at 110 and increasing to 350 V_{rms} in steps of 20 V (a total of 12 conditions). For each condition, a fresh drop was dispensed and the cycle was repeated 50 times on a set of four unused electrodes. The complete set of conditions was tested using 12 columns on single device, eliminating any intra-device variability and cumulative effects between conditions. Device impedance was estimated every 10 ms using Equations 2 and 3, and the impedance was attributed solely to the combined capacitance of the dielectric and hydrophobic layers; therefore, the total capacitance of the device was calculated using the equation:

$$C = \left|\frac{1}{2\pi f Z(f)}\right| \quad (4)$$

If each drop is assumed to take the square shape of an electrode, then at time t, its position along the direction of travel, $x(t)$, is related to the total device capacitance by the expression:

$$x(t) = \frac{C(t) - L^2 c_{filler}}{L(c_{liquid} - c_{filler})} \quad (5)$$

where $C(t)$ is the capacitance at time t, L is the width of the square electrodes, and c_{liquid} and c_{filler} are the capacitance per unit area of an actuated electrode covered in liquid and filler media (e.g., air or oil), respectively. Differentiation of Equation 5 yields the instantaneous velocity:

$$\frac{dx(t)}{dt} = \frac{d}{dt}\frac{C(t) - L^2 c_{filler}}{L(c_{liquid} - c_{filler})} \tag{6}$$

This derivative was approximated on the Arduino by the finite difference of the capacitance time series.

Amplifier-loading effects

A 0.5 V_{rms} input signal (100 V_{rms} output, assuming a DC gain of 200) was swept between 0.1 and 30 kHz in 30 steps equally spaced on a $\log_{10}$ scale. Peak-to-peak voltage measurements were collected using the Arduino for each frequency (10 measurements, 10 ms duration each), and the amplifier output voltage, V_{total}, was calculated according to Equation 2. The experiment was repeated with 0, 1, 2 and 3 high-voltage switching boards connected to the amplifier with all switches in their off state. The same experiment was repeated with amplifier-gain compensation; in this case, the target voltage was set to 100 V_{rms} and the Arduino modulated the amplitude of the input signal every 10 ms to maintain the target output.

To measure the effect of device loading, three high-voltage switching boards were connected to the system and three reservoir electrodes of the DMF device were each loaded with 10 µl of DI water. A 0.5 V_{rms} signal with a driving frequency of 10 kHz was applied to the amplifier input and 0, 1, 2, or 3 electrodes were actuated simultaneously. In each case, the amplifier output was measured 100 times over a period of one second. The same conditions were applied with amplifier-gain compensation (i.e., modulation of the input voltage every 10 ms to maintain a target output of 100 V_{rms}).

Force normalization experiments

Drops of DI water were translated across four electrodes as in the velocity experiments with a driving frequency of 10 kHz and voltages of 60, 80 and 100 V_{rms} (devices with bottom-plates coated with 2.2 μm Parylene-C) and 110, 130, 150, 170 and 190 V_{rms} (devices with bottom-plates coated with 6.2 μm Parylene-C). Drop velocity was recorded every 10 ms and the capacitance per unit area of liquid- and air-covered electrodes was measured by the control board.

References

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