Supplementary Materials for

Demonstration of electric micropropulsion multimodality

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This PDF file includes:

Supplementary Materials and Methods
Figs. S1 to S3
References
Supplementary Materials and Methods

Characterization of discharge characteristics of the thruster

A more detailed electrical circuit of the thruster is given in the Fig. S1. The first-stage power processing unit (PPU) consisted of a 25 V dc power supply (BK Precision 1550), a polar capacitor $C_1 = 2.2 \text{ mF}$, an inductor $L = 550 \mu \text{H}$ with ferrite core, and an IGBT (IXYH50N120C3). After applying to the IGBT gate a control rectangular signal (with amplitude of 5 V, 0.35 ms pulse width and variable pulse repetition rate $f$ up to 20 Hz), the first-stage PPU formed a peak of voltage with amplitude of up to 1200 V and a duration of several tens of microseconds. This voltage, applied between anode and cathode of the thruster, resulted in the formation of the preliminary arc discharge plasma with the first-stage discharge voltage $U_1(t)$ (measured by Tektronix P6015 high-voltage probe) and discharge current $I_1(t)$ (measured by Pearson model 110 current monitor). The second-stage discharge with voltage $U_2(t)$ (measured by Tektronix P2220 probe) and current $I_2(t)$ (measured by Pearson model 110 current monitor) is ignited due to the dc $U_{MPD}$ voltage (up to 180 V, stabilized by a polar capacitor $C_2 = 10.7 \text{ mF}$) applied between the cathode and the second-stage MPD electrode. All waveforms of current and voltage were displayed, digitized and stored for further processing after averaging over 256 single waveforms using a digital TDS3014C oscilloscope.

Average powers dissipated in the first $P_1$ and the second $P_2$ stages of the thruster were calculated using the formulas:

$$P_1 = \int_0^{\tau_1} I_1(t)U_1(t)dt,$$

$$P_2 = \int_0^{\tau_2} I_2(t)U_2(t)dt,$$

where $\tau_1$, $\tau_2$ are the pulse widths of the first- and second-stage instantaneous powers. The errors for $P_1$, $P_2$ were estimated as standard deviations $\delta(P_1)$, $\delta(P_2)$ over up to 6 experimental trials.

The total power $P$ dissipated in the both stages within single experimental trial was estimated by summarizing $P_1$ and $P_2$:

$$P = P_1 + P_2$$

The error for $P$ was estimated using the standard deviations $\delta(P_1)$, $\delta(P_2)$ for the first and second-stage powers:

$$\delta(P) = \sqrt{\delta^2(P_1) + \delta^2(P_2)}.$$ 

The final value of the total power $\langle P \rangle$ was obtained as the average value of all experimental total powers $P$ obtained at the same experimental conditions.

Thrust and thrust-to-power ratio

The average thrust was measured by placing the thruster directly on the movable arm of the torsional thrust stand (see the Fig. S2). Thruster firing caused the deflection of the movable arm around its axis of rotation; this deflection was measured by the laser sensor. Using the set of fins placed on high-precision scale (identical to the fins placed on the end of the thrust stand arm), this deflection was recalculated to a force (i.e. thrust). More detailed information regarding thrust stand measurements are given in our previous work (25). The final value of the average thrust $\langle T \rangle$ then was estimated as the
average value of thrusts \( T \) obtained within up to 6 experimental trials at the same experimental parameters. The error of thrust \( \langle T \rangle \) was estimated as a standard deviation \( \delta(T) \).

The thrust-to-power ratio (TPR) was measured by dividing the thrust value \( \langle T \rangle \) over the total power \( \langle P \rangle \):

\[
\langle TPR \rangle = \frac{\langle T \rangle}{\langle P \rangle}
\]  
(5)

The error for TPR was estimated using relative errors of the standard deviations for thrust \( \delta(T) \) and total power \( \delta(P) \):

\[
\delta(TPR) = \langle TPR \rangle \left[ \sqrt{\left( \frac{\delta(T)}{\langle T \rangle} \right)^2 + \left( \frac{\delta(P)}{\langle P \rangle} \right)^2} \right],
\]  
(6)

where \( \langle TPR \rangle, \langle T \rangle \) and \( \langle P \rangle \) are the average values of thrust-to-power ratio, thrust and power for the same experimental conditions.

**Exhausting ion velocity**

The exhausting ions velocity was determined by the time-of-flight method using experimental setup described in details in our previous study (35). Briefly, the thruster was fired with the plasma towards the two negatively-biased electrodes (first one is copper grid, the last one is stainless steel plate) placed at the distances \( s_{12} = 17 \text{ cm} \) and \( s_{13} = 37 \text{ cm} \) from the thruster exhaust. Once ions arrive at the electrode, they produce a pulsing current in the circuits of the each electrode. The ion velocity within single experiment \( v \) was estimated as:

\[
v = \left[ \left( s_{12}/t_{12} \right) + \left( s_{23}/t_{23} \right) + \left( s_{13}/t_{13} \right) \right]/3,
\]  
(7)

where \( s_{12} \) is the distance between the thruster exhaust and the first electrode, \( s_{23} \) is the distance between electrodes, \( s_{13} \) is the distance between the thruster exhaust and the last electrode, \( t_{12}, t_{23} \) and \( t_{13} \) are respective time delays between maxima of the first-stage discharge current and ionic currents from each electrode. The final value of the ion velocity \( \langle v \rangle \) was estimated as the average value of velocities \( v \) obtained within up to 6 experimental trials at the same experimental parameters. The error of ion velocity \( \langle v \rangle \) was estimated as a standard deviation \( \delta(v) \).

**Specific impulse and energetic efficiency**

Specific impulse \( \langle I_{sp} \rangle \) was estimated from the ion velocity \( \langle v \rangle \) as \( \langle I_{sp} \rangle = \langle v \rangle / g_0 \), where \( g_0 \) is the gravitational acceleration at the surface of the earth. The error of specific impulse \( \delta(I_{sp}) \) was estimated from the error of ion velocity \( \delta(v) \) as \( \delta(I_{sp}) = \delta(v) / g_0 \).

Energetic efficiency \( \eta \) was estimated using the values of thrust, ion velocity and total power as

\[
\eta = \frac{\langle T \rangle \langle v \rangle}{\langle P \rangle},
\]

**Mass flow rate**

The mass flow rate was estimated according to the formula \( \langle \dot{m} \rangle = \langle T \rangle / \langle v \rangle \) under assumption that all exhausting heavy particles are the ions which produce the thrust. The error in determination of mass flow rate was estimated as

\[
\delta(\dot{m}) = \langle \dot{m} \rangle \left[ \sqrt{\left( \frac{\delta(T)}{\langle T \rangle} \right)^2 + \left( \frac{\delta(v)}{\langle v \rangle} \right)^2} \right].
\]
**Total ion current measurement**

Total ion current $I_i(t)$ was measured by placing the thruster inside a semispherical negatively-biased (-100 V) electrode (25, 35). Then, the fractions of pulse-average total current $\langle I_i \rangle$ and charge $\langle Q_i \rangle$ of ions expelled by the thruster were estimated using the formulas:

$$\frac{\langle I_i \rangle}{\langle I_1 \rangle + \langle I_2 \rangle} = 100\% \times \left[ \frac{1}{\tau_i} \int_0^{\tau_i} I_i(t)dt \right] \left/ \left( \frac{1}{\tau_1} \int_0^{\tau_1} I_1(t)dt + \frac{1}{\tau_2} \int_0^{\tau_2} I_2(t)dt \right) \right]$$

(8)

$$\frac{\langle Q_i \rangle}{\langle Q_1 \rangle + \langle Q_2 \rangle} = 100\% \times \left[ \int_0^{\tau_i} I_i(t)dt \right] \left/ \left( \int_0^{\tau_1} I_1(t)dt + \int_0^{\tau_2} I_2(t)dt \right) \right]$$

(9)

where $\tau_i$ is the duration of the total ion current pulse, $Q_1$ and $Q_2$ are the charges of the first- and second-stage discharge currents. The error in determination of the mentioned ratios was estimated to the respective standard deviations.
Fig. S1. Electrical circuit of the two-stage µCAT-MPD thruster.
Fig. S2. Schematic view of the setup for the direct thrust measurement.
Fig. S3. Original (non-processed) images of the side surfaces of the cathodes after firing of the first stage only (upper image), and together with the second stage (lower image), within the single pulse.
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