Metal-Air Harvester

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What needs energy?

Internet of Things (IOT)

Robots

IOT devices is projected to grow from 27 billion in 2017 to 125 billion by 2030.

The endurance and performance of most robots are limited by their ability to store energy.

Spot

Quadcopter

HAMR Microrobot

1 min. as shown. 4.5 min. max
How do we provide energy?

Energy stored in an on-board battery or fuel cell.

- 5 to 8% energy density growth per year
- In 9 – 15 years, our micro-robots will operate for 2 minutes and our drones will fly for 30 minutes

Harvesting energy from the local environment

- Low power
- Periodic delivery
- Require specific environments.

Toolstation.com

Zhao et al., *IEEE Access*, vol. 5, 2017
A new source of harvested energy: metal

- Aluminum
  - 38 kJ/g
  - 84 MJ/L
- Iron
  - 5 kJ/g
  - 40 MJ/L
- Gasoline
  - 34 MJ/L
- Lithium ion battery
  - ~2 MJ/L

- M1A1 tank
  - 3 x 10^{11} J of energy

- Approximate food energy consumed by an average human in an 80-year lifetime.
- Energy used to power an average US household car for ~4 years.

If this robot were to operate on a 30" aluminum stop sign, where the MAS can extract 316 mWh/cm^2, the total energy available would be 1,500 Wh, about 23X greater than a $37 laptop battery and enough to power a 1 mW sensor for 171 years. Corrodes about 300 μm of Al, or 15% of the stop sign.
The benefit of harvesting metal: Metal-Air Harvester

Typical battery design

- Anode (Oxidation)
- Electrolyte
- Cathode (Reduction)

Electronics

THE FUTURE
The benefit of harvesting metal: Metal-Air Harvester

Typical battery design

Air battery design

\[ \text{Zn} + 4\text{OH}^- \rightarrow \text{Zn(OH)}_4^{2-} + 2e^- \quad (E_0 = -1.25 \text{ V}) \]
\[ \text{Zn(OH)}_4^{2-} \rightarrow \text{ZnO} + \text{H}_2\text{O} + 2\text{OH}^- \]

Catalyst for reducing air

- Oxygen is the cathode
- Oxygen is free

\[ \frac{1}{2} \text{O}_2 + \text{H}_2\text{O} + 2e^- \rightarrow 2\text{OH}^- \quad (E_0 = 0.34 \text{ V \ pH=11}) \]
The benefit of harvesting metal: Metal-Air Harvester

Typical battery design

Air battery design

Zn + 4OH\(^{-}\) → Zn(OH)\(_4\)^{2-} + 2e\(^{-}\) \(E_0 = -1.25\) V

Zn(OH)\(_4\)^{2-} → ZnO + H\(_2\)O + 2OH\(^{-}\)

Catalyst for reducing air

- Oxygen is the cathode
- Oxygen is free

1/2 O\(_2\) + H\(_2\)O + 2e\(^{-}\) → 2OH\(^{-}\) \(E_0 = 0.34\) V pH=11

The device only carries the electrolyte and cathode current collector
The benefit of harvesting metal: Metal-Air Harvester

Current technology

- Electronic payload
- Commercial thin film battery

1 mWh/cm² energy density

Future metal energy scavenger

- Electronic payload
- New metal energy scavenger cell

Two design paths

1. "eat" through surface
2. "eat" across surface

Cell movement

Up to 1,000 mWh/cm² energy density for a 1 mm thick aluminum plate

~80-300 mWh/cm² * (area of plate) energy density for a 100 um thick discharge

The benefit of harvesting metal: Metal-Air Harvester

- Electronic payload
- New metal energy scavenger cell

- Aluminum or other metals

Cell movement

Up to 1,000 mWh/cm² energy density for a 1 mm thick aluminum plate

~80-300 mWh/cm² * (area of plate) energy density for a 100 um thick discharge
The MAH can power electronics by consuming metal from external surfaces and breathing oxygen from the air.
Zinc surface Performance

- MAS penetrates ~110 μm into the surface
- 83 mWh/cm²

PVA = poly(vinyl alcohol)
PAM = polyacrylamide

Graphs showing voltage (V vs. Zn) and power density (mW/cm²) vs. current density (mA/cm²) for PVA and PAM.

Specific Capacity (mAh/g\text{MAS})

5 mA/cm²
Performance

- MAS on Al penetrates ~285 μm into the surface
  - 316 mWh/cm²

![Graphs showing voltage and power density vs specific capacity and current density for different systems.](image-url)
Pourbaix diagram

Eh / V vs. pH

Zn$^{2+}$

ZnO(s)

ZnO$_2^-$

Zn(s)

E in V vs. S.H.E.

Al$^{3+}$ (corrosion)

Al$_2$O$_3$ (passivity)

AlO$_2^-$ (corrosion)

Al (immunity)

5 mA/cm$^2$

Specific Capacity (mAh/g)
Pourbaix diagram
• MAS can power robots, vehicles, and electronics by traversing metal surfaces.

• Toy-vehicle driving in a circle on top of an aluminum sheet that is powering the vehicle.
The ability to move and extract energy from metals makes the effective energy density of our technology very high.

• Like you, the technology does need to drink water (at least 0.34 g/Ah on aluminum)