

PROCEEDINGS

Electrochemical Pneumatic Battery for Compact, Efficient, and Silent Robotic Actuation

Junyu Ge¹, Yifan Wang¹ and Hong Li^{1,2,*}

¹School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, 639798, Singapore

²CINTRA CNRS/NTU/THALES, UMI 3288, Research Techno Plaza, Singapore, 637553, Singapore

*Corresponding Author: Hong Li. Email: ehongli@ntu.edu.sg

ABSTRACT

The advancement of untethered and adaptive robotic systems necessitates the development of compact, efficient, and silent pneumatic power sources [1,2]. Traditional pneumatic actuation relies on bulky compressors or external gas reservoirs, limiting their practical applications in mobile and autonomous systems [3,4]. This work presents a novel electrochemical pneumatic battery (EPB) that exploits electrochemical driven gas generation to achieve controlled and energy-efficient pneumatic actuation, offering a viable alternative to conventional air supply methods.

The EPB operates through an electrochemical redox mechanism based on a zinc-oxygen battery [5–7], enabling reversible gas storage and controlled pressure modulation. This motor-free and self-contained system eliminates the reliance on mechanical pumps, allowing for seamless integration into robotic platforms. The battery design incorporates zinc nanowire anodes which is fabricated with our rapid room temperature ultrasonic nanoimprinting technique [8], which enhance reaction kinetics, improve gas generation efficiency, and lead to faster response times, higher energy density, and extended operational lifespan. Unlike conventional pneumatic pumps which only can provide vacuum or high pressure, EPB achieves a pressure range from -0.98 to 7 bar, offering both positive and negative pressure control, making it versatile for robotic applications requiring both vacuum and inflation-based actuation.

The applicability of EPB is demonstrated across various robotic domains, including both soft and rigid robotic actuators, modular robotic systems, and grippers, as shown in Fig.1. A detailed evaluation of its pressure regulation, energy consumption, cyclic stability, and scalability is conducted, providing insights into its practical deployment in wearable robotics, industrial automation, and bio-inspired systems. Its capability to drive grippers, flexible actuators, and morphing structures without external air sources significantly improves system mobility and efficiency. The system's flexibility allows its integration into smart materials and robotic matter, where structural components themselves can serve as pneumatic power sources, enabling compact and autonomous robotic designs.



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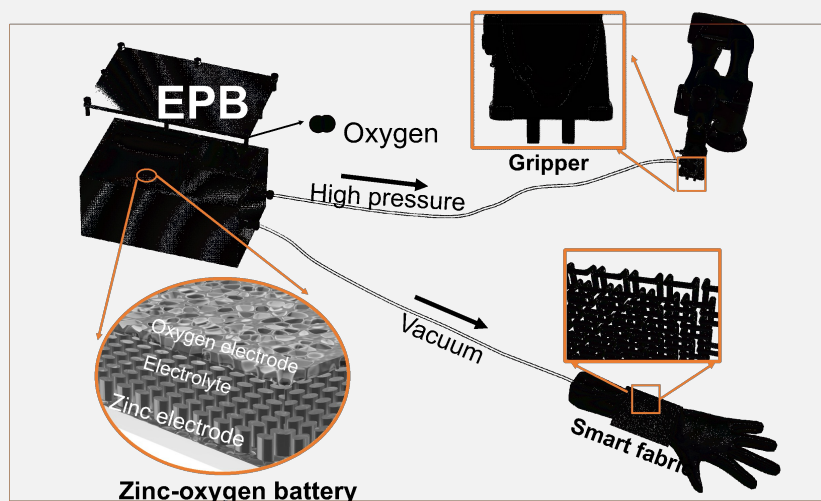


Figure 1: Schematics of EPB structure and applications

Comparative analysis with traditional pneumatic sources highlights EPB's significant reduction in energy expenditure, noise generation, and footprint, making it an ideal solution for untethered robotic applications. Furthermore, its compatibility with emerging robotic technologies, such as origami-inspired actuators [8], artificial muscles [9], and hybrid soft-rigid systems [10], expands its potential applications beyond traditional robotic actuation.

By integrating electrochemical pneumatics with robotic architectures, this work presents a transformative step toward the realization of self-sufficient robotic actuation systems. Future research will focus on optimizing electrochemical reaction rates, improving the durability of electrode materials, increasing gas generation efficiency, and exploring hybrid actuation paradigms to further expand its capabilities in next-generation robotics. Additionally, efforts will be directed toward developing miniaturized and flexible EPBs for biomedical and assistive robotic applications, offering a sustainable and energy-efficient alternative to conventional pneumatic actuation.

KEYWORDS

Electrochemical pneumatic battery; adaptive robotic actuation; ion-driven pneumatics; untethered robotics; wearable robotics; energy-efficient automation

Acknowledgement: The authors would like to acknowledge the contributions of collaborators (Dr. Yucheng Zhao) who provided insights and technical support throughout this research.

Funding Statement: This work was supported by A*STAR Science & Engineering Research Council MTC IRG funding (M21K2c0118), Ministry of Education Singapore (award no.MOE-T2EP50221-0002), and Delta-NTU Corporate Lab for Cyber-Physical Systems, with funding support from Delta Electronics. and National Research Foundation Singapore (NRF).

Conflicts of Interest: H.L. is an inventor on a patent application related to this work, filed by Nanyang Technological University Singapore (application nos. 202180011805.4 and 11202252422A). J.G. and H.L. are inventors on a patent application related to this work, filed by Nanyang Technological University Singapore (publication no. WO 2022/045965 A1).

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