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Perspectives on Biomedical Piezoelectric Nanogenerators: A Roadmap and Benchmark

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Abstract: The exponential rise in Internet-of-Things devices has highly impacted the domain of medical implants. The latter are a pillar of modern medicine and enable the treatment of many diseases and patient-specific monitoring. However, reliance on batteries that must be replaced through invasive interventions or recharged regularly places stress on the patient and may reduce patient outcomes. Energy harvesting using implantable nanogenerators has shown promise as a way to extend the lifetime of battery-driven implants or even to replace batteries in devices. This paper outlines a specific benchmark challenge and the required directions for powering deep-brain stimulators.

I. Introduction

The exponential rise of Internet of Things (IoT) devices will lead to a tremendous increase in their energy demand. Specifically, medical implants – indispensable in modern medicine – rely on primary, or secondary batteries, which are a bottleneck that can be addressed by energy harvesting [1]. It would eliminate the need for regular battery replacements, leading to greater health benefits and patient comfort [2]. For this reason, many researchers investigate implantable nanogenerators (NGs) that convert energy from various sources within the human body and its environment to power other implants. This paper outlines a roadmap for fully implantable energy harvesters based on knitted piezoelectric filaments and a realistic benchmark derived the application of deep-brain stimulation (DBS).

I.I. Energy Harvesting for Biomedical Implants

The term energy harvesting (EH) refers to the conversion of energy, typically into electrical energy. Phenomena that are utilized are, e.g., thermo-, pyro-, tribo-, magneto-, and piezoelectric effects [1]. The current state of the art shows that piezoelectric energy harvesting, i.e., the conversion of mechanical energy into electrical energy, yields devices with the highest reported power densities [3].

In the context of biomedical applications, polyvinylidene fluoride (PVDF), a piezoelectric polymer, and its co-polymers have shown to be promising candidates in terms of biocompatibility and processing [4], [5]. A high percentage (70 – 80%) of the material must be in the crystalline β-phase, which provides the highest dipole moment and therefore the highest piezoelectric effect due to its molecular geometry [3]. The material's structure indirectly affects the amount of β-phase due to the processing. Consequently, thin films and fiber-based structures are typical choices for the material [5], [6]. These are then placed between electrodes containing, e.g., silver to form a planar energy harvesting device.

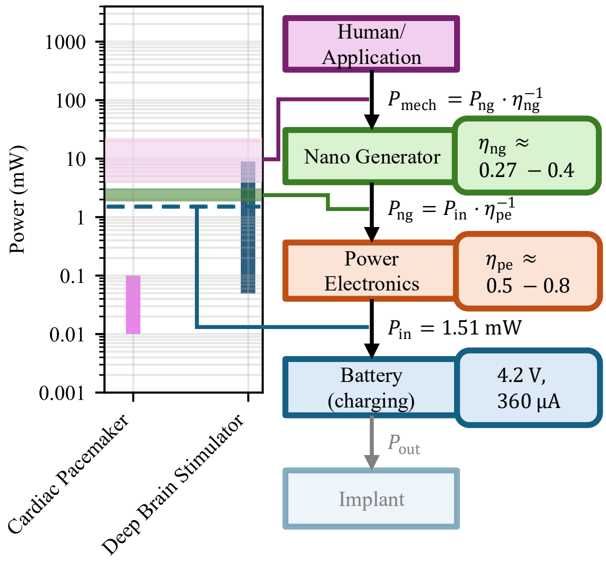

Figure 1: Problem formulation of energy harvesting for deep-brain stimulators. An outline of the power demands of each component is shown. P_{in} is the power required to charge the battery. P_{ng} is the power the nano generator must provide. η_{pe} and η_{ng} are the estimated efficiencies of all power electronics and of the nano generator. P_{mech} is the required mechanical power. The ranges for the cardiac pacemaker and DBS are taken from [1].

II. Nano Generator Benchmark

In the current state of the art, there are no unified, accessible benchmarks for the outlined challenge of medical implants. The reasons for this could be that medical-grade secondary batteries are hard to access and expensive due to strict regulations and the different requirements for power management units, which must be tailored to the NGs.

Still, a benchmark is required to demonstrate the actual impact on clinical research and to compare different types of NGs. Figure 1 shows the suggested benchmark, including battery specifications and power flow for a deep brain stimulator. The chosen secondary battery is a consumer grade lithium/ion battery (RS PRO LIR2430, nominal voltage 2.75 V, capacity 60 mAh). This battery is similar to that of implanted rechargeable deep-brain stimulators, which last for seven days before needing to be recharged via wireless power transmission. The maximum charging voltage according to the data sheet is 4.2 V, and the required charging current, calculated as capacity divided by seven-day run time, is 360 μA. This leads to an average power demand $P_{\text{in}} = 1.51\,\text{mW}$. However, a piezoelectric NG generates a random AC signal (depending on the application), which requires specialized rectifiers and DC/DC conversion. An estimated efficiency of η_{pe} leads to a required power output of 2.0 mW to 3.5 mW (P_{ng}). The power output depends heavily on the application and the efficiency of the proposed NG. This is theoretically outlined in the following section.

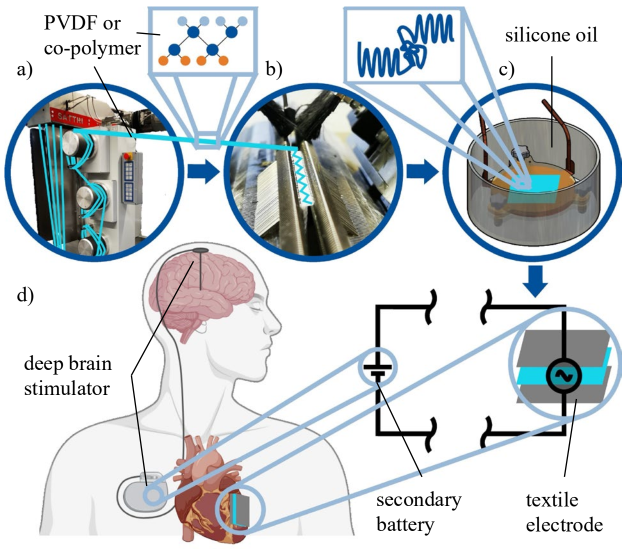

Figure 2: The outlined roadmap. The melt-spinning machine in a) is used to produce multifilament yarn with a high β-phase content. The yarn is knitted on a flat-knitting machine (b) and polarized in a custom-made silicone bath under high-voltage electrical fields. The final device depicted in d) is envisioned, but not limited to, powering medical implants, e.g., deep-brain stimulators.

III. A Roadmap to Implantable, Textile-based Nano Generators

Knitted structures from multifilament yarns have several advantages. The melt-spinning process increases the share of crystalline β-phase in the material due to mechanical stretching. The NG becomes highly stretchable compared to films, which addresses one of the main disadvantages of PVDF-based NGs – the material's brittleness. The production is scalable and can be achieved using established industrial production lines. The NGs from knitted composite yarn show excellent power densities. Recent work has produced energy harvesters from a PVDF/nanocomposite monofilament [5]. This research will continue using a multifilament melt-extruder and a flat-knitting machine (see Figure 2). To align the crystalline phase in the material, a polarization device is being developed that uses strong electric fields in silicone oil at 80 °C. The knitted structure is placed between two silver-based textile electrodes.

With similar devices, preliminary works have achieved an efficiency η_{ng} of 27 to 40 % [7]. In conclusion, this would require a mechanical power input between 4.73 mW and 11.2 mW, which, e.g., is approximately 1.2 % of the power the human heart pumps per cardiac cycle (hemodynamic power output, 60 bpm, mean pressure of 100 mmHg, 70 ml/stroke) [8]. Considering that this is far below the variation in loads a heart endures during the day, at least from this point of view, the heart could be a potential power source.

IV. Conclusion and Outlook

Energy harvesting will likely become a key technology in the future IoT world. With recent advances, the proposed benchmark and application have become feasible and will be the focus of our continued research. While the estimates in this paper provide first insights into expected results, other considerations regarding mechanical deformations, physiology, and biocompatibility have been omitted. These must be accounted for to prepare the first clinical studies.

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Author's statement

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