Politecnico di Torino

Doctoral Program in
Electrical, Electronics and Communications Engineering
(37^{th} Cycle)

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Thesis Summary

Advancing Next-Generation Active Implantable Medical Devices

System Design and Integration for Long-Term Therapeutic Applications

1. Context and Motivation

Active Implantable Medical Devices (AIMDs) have evolved from essential life-support technologies like pacemakers to multifunctional, connected platforms capable of delivering long-term therapies directly within the body. Their promise lies in enabling personalized and adaptive healthcare – but realizing this potential requires addressing complex engineering challenges, particularly when designing for chronic use.

The demands placed on AIMDs—miniaturization, biocompatibility, power autonomy, and wireless communication—are deeply interdependent. Many experimental systems remain constrained to short-term studies due to limitations in energy availability or system reliability. One of the key bottlenecks in the clinical translation of implantable drug delivery systems is the lack of sustainable, autonomous operation over extended periods.

This thesis responds to that need by advancing the *Nanochannel Delivery System (nDS)*: a refillable, programmable implantable device intended for long-term administration of therapeutics. Building on prior work validating the drug release mechanism, this research focuses on the design and integration of a wireless power and control system, enabling safe and repeatable recharging in freely moving animal models without requiring externalized components or invasive procedures.

2. Methodology and System Development Strategy

The development approach adopted a systems engineering perspective, emphasizing real-world constraints and translational readiness from the outset. A modular, iterative de-

sign strategy was used to develop the core components of the platform, comprising an implantable unit and a wearable external controller, connected through bidirectional wireless communication and supported by adaptive power management.

Rather than introducing novel release actuation methods, the focus was on ensuring that the already-established delivery mechanism could function reliably in long-term, mobile conditions – which necessitated the integration of a rechargeable power supply, closed-loop wireless power transfer (WPT), and robust firmware for control and telemetry.

3. System Architecture and Functional Elements

The system (Fig. 1) consists of two main subsystems:

- **Implantable Unit:** including the drug delivery actuation system, a rechargeable lithium battery and electronic circuits. A power management IC allows inductive energy harvesting and regulation, while a microcontroller enables system control, based on Bluetooth Low Energy (BLE) communication. All components are encapsulated in a biocompatible, subcutaneous format suitable for rodent implantation.
- **External Transmitter (Backpack System):** Mounted on the animal's back, this unit includes a transmission coil, a microcontroller with BLE interface, and a programmable power driver. Its primary role is to wirelessly deliver energy to the implant and to adapt transmission parameters based on implant feedback.

A key innovation lies in the closed-loop WPT control strategy. The implant periodically sends voltage telemetry via BLE to the external unit, which then adjusts its output power to optimize recharge efficiency and maintain system safety. This feedback loop ensures reliable energy transfer despite typical misalignments or motion-related disruptions common in animal experiments and in-vivo settings.

The architecture was validated through benchtop testing of inductive coupling and safety limits, and in vivo experiments in freely moving rodents over multi-week periods. The system demonstrated stable power transfer and functional robustness during natural movement.

4. Broader Impact and Generalization

The system developed in this thesis addresses a critical gap in the chronic use of implantable devices by providing a reliable infrastructure for wireless power, remote control, and long-term functionality. By integrating commercially available technologies into a robust and scalable platform, the work provides a model not only for drug delivery systems but also for a wider class of AIMDs facing similar power and integration constraints.

Conclusion

This thesis contributes to the field of implantable medical electronics by advancing a complete, validated system that enables the chronic deployment of programmable drug delivery in animal models. Through a tightly integrated design combining wireless power transfer, BLE-based telemetry, and real-world validation, it lays the groundwork for the next generation of adaptive therapeutic implants.

The demonstrated solution bridges the gap between experimental prototypes and trans-

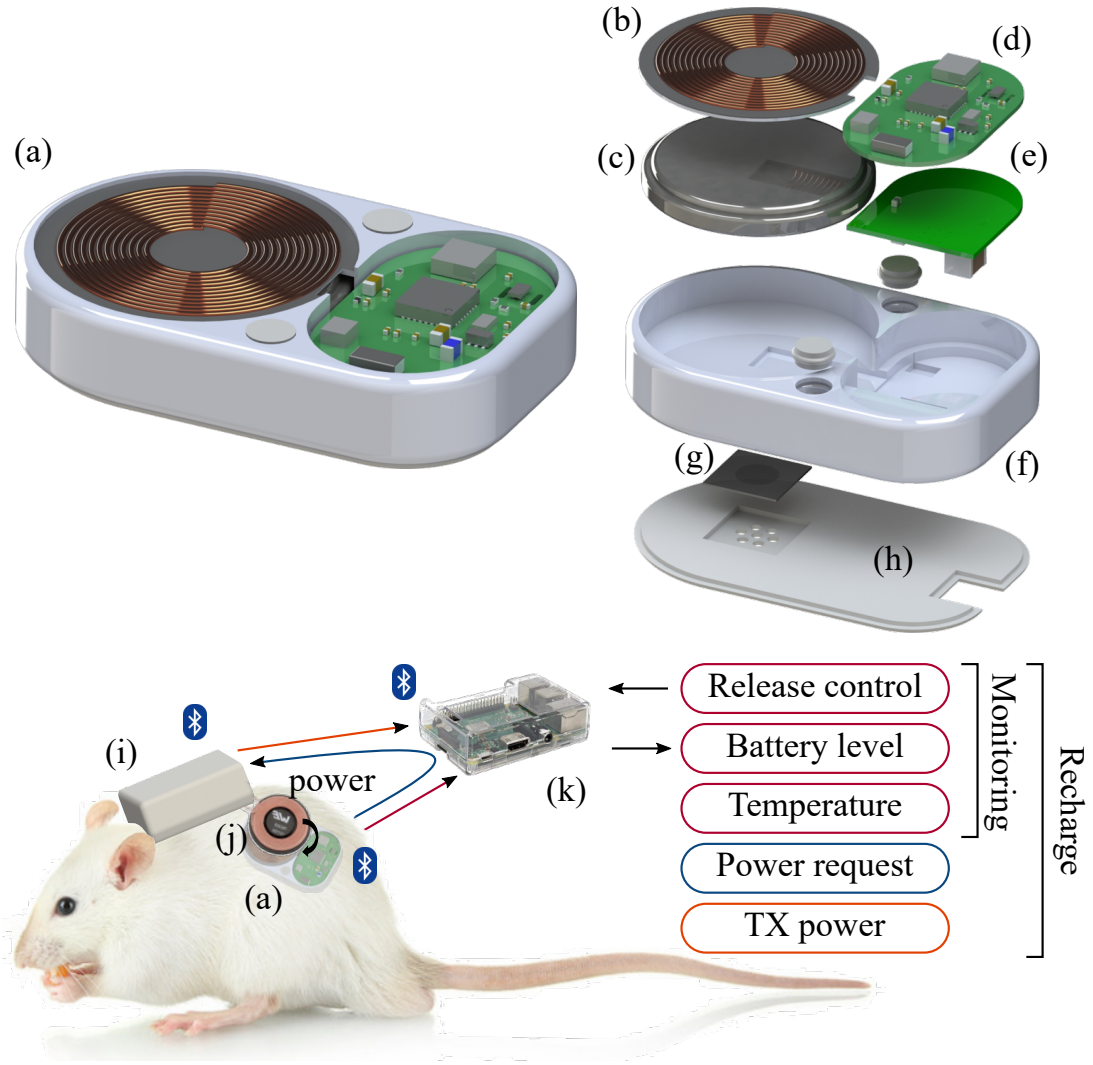

Figure 1: Overview of the developed system for in-vivo validation: a. implant; b. power receiver coil; c. rechargeable battery; d. device control circuit; e. power management circuit; f device case; g. drug release actuator; h. reservoir cover; i. wearable transmitter ppack; j. transmitter coil; k. Raspberry Pi for remote control.

lationally viable systems, supporting the broader vision of unobtrusive, long-term interventions tailored to the physiological and therapeutic needs of individual patients.