Abstract

Quantitative assessment of human movement plays a fundamental role in rehabilitation, clinical decision-making, sports science, and long-term health monitoring. Although optical motion-capture systems provide highly accurate biomechanical measurements, their dependence on dedicated laboratory infrastructure prevents their applicability to real-world and home-based settings. Wearable inertial sensing systems offer a promising alternative by enabling continuous and ambulatory monitoring. However, their widespread adoption requires overcoming challenges related to low-power embedded implementation, wireless communication, multi-sensor synchronization, and robust biomechanical signal processing.

This thesis presents the development of Apollux, a wearable wireless sensing platform designed for real-time biomechanical monitoring based on inertial measurement units (IMUs). The work adopts a system-level approach that integrates embedded hardware and firmware, Bluetooth Low Energy (BLE) communication, distributed synchronization, and motion-processing algorithms into a unified framework suitable for wearable applications. The dissertation is organized in three primary contributions.

The first contribution extends the Apollux platform with inertial sensing capabilities through the development of firmware, acquisition modes, and software infrastructure supporting real-time wireless streaming and local data logging while maintaining low-power operation. Power characterization demonstrated an estimated operating time exceeding four days during continuous accelerometer and gyroscope data streaming. These developments transform the original platform into a modular multimodal sensing system capable of supporting biomechanical monitoring in laboratory and ambulatory environments.

The second contribution introduces SharkTooth, a scalable synchronization algorithm for BLE-based wireless body sensor networks. Unlike conventional approaches

requiring dedicated synchronization messages or modifications to the BLE protocol, SharkTooth exploits timestamps embedded in standard data packets and compensates for communication-induced timing uncertainty. Experimental validation demonstrates sub-millisecond synchronization accuracy in networks comprising up to twelve simultaneously connected wearable nodes, providing a practical solution for temporally coherent acquisition in distributed biomechanical and electrophysiological applications.

The third contribution presents a complete joint angle estimation pipeline tailored to muscle-aligned wearable IMUs. The proposed methodology includes calibration, orientation estimation, heading correction, and biomechanical joint modeling to estimate upper- and lower-limb kinematics while preserving sensor placements compatible with simultaneous surface electromyography acquisition. Validation against a reference optical motion-capture system demonstrates median RMSE values of 2.71° for the knee and 2.75° for the elbow, while the proposed heading correction significantly improves robustness against heading drift and placement-related offsets.

Overall, this dissertation demonstrates that reliable real-time biomechanical monitoring depends on the co-design of wearable hardware, embedded software, wireless communication, temporal synchronization, and signal-processing algorithms. The proposed framework establishes a scalable foundation for multimodal wearable systems intended for rehabilitation, tele-rehabilitation, clinical assessment, sports science, and long-term monitoring of human movement, bridging the gap between laboratory-grade biomechanical analysis and continuous monitoring in real-world environments.