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Electronic Instrumentation for Biological Signal Acquisition

From Neural Interfaces to Cardiovascular Health Monitoring

By

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Declaration

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Electronic Instrumentation for Biological Signal Acquisition

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The motivation of this thesis is to translate advances in sensing, electronics, and embedded processing into biomedical technologies that are more accessible, efficient, and responsive to real needs. This requires complete instruments to be designed around the biological information to be measured rather than by optimizing isolated components. An application-driven methodology is therefore applied to multichannel extracellular recording from *in vitro* neuronal cultures and non-invasive arterial pulse-wave monitoring.

The main contribution is an accessible event-driven neural acquisition platform for passive Microelectrode Arrays (MEAs). Extracellular spikes are detected in hardware and represented through channel identity and millisecond-scale timing, avoiding continuous sampling when waveform morphology is not required. The platform is modular and comprises a low-noise analog front end, a motherboard with the threshold-based event-driven core and two versions of control units: a 15-channel microcontroller unit, used as proof of concept, and a 60-channel Field-Programmable Gate Array (FPGA) unit, used as the ultimate implementation. Preliminary tests demonstrated feasibility of microvolt-scale signal acquisition with an input-referred RMS noise below $10\,\mu V$. At $SNR_{lin} = 10$, the MCU-based version achieved an aggregate F_1 score of approximately 0.98 up to 300 Hz, while the FPGA-based implementation maintained F_1 values of approximately 0.95–0.97 up to 200 Hz. Thanks to the proposed approach, the ideal continuous sampling with 12-bit payload at $10\,kS\,s^{-1}$ was reduced by 99.1% for 15 channels and 98.7% for 60 channels. Mean system latency ranged from 0.34 ms to 1.45 ms. The complete prototype had an estimated hardware cost of approximately USD 3,000, excluding development and personnel costs. Its main trade-off is the loss of waveform morphology, while complete end-to-end biological validation remains necessary future work.

The second contribution was a pulse-wave monitoring platform integrating a custom rGO-R1 piezoresistive sensing material with a flexible PCB. A mechanical interface and embedded acquisition electronics were developed around the sensor to assess its feasibility for acquiring superficial arterial pressure pulses. Sensor-level characterization showed a low-pressure sensitivity of $0.281\,kPa^{-1}$ and favourable

short-term cyclic stability. The platform also acquired single-site and simultaneous carotid–femoral pulse waves. Although the physiological evaluation was preliminary, the identified structural and operating limitations guided the development of the subsequent wearable system.

The third contribution followed the rGO-R1-based sensing platform and addressed its limitations by adopting more stable and accessible commercial Force-Sensing Resistors (FSRs). These sensors were integrated into two synchronized wireless wearable modules for simultaneous carotid and femoral pulse-wave acquisition and carotid–femoral Pulse Wave Velocity estimation. Hardware synchronization preserved the relative timing between the two modules independently of Bluetooth Low Energy transmission. In 101 volunteers, comparison with SphygmoCor yielded Pearson correlation and Lin concordance coefficients of 0.823, together with a mean paired difference of $0.03\,\mathrm{m\,s^{-1}}$. The mean within-subject standard deviation was $0.63\,\mathrm{m\,s^{-1}}$ for the wearable system and $0.40\,\mathrm{m\,s^{-1}}$ for the reference device. These results support the feasibility of supervised wearable PWV assessment, while indicating that sensor fixation, placement, and waveform-quality control require further improvement.

The main strength of the thesis is the consistent use of application-level information requirements to guide complete biomedical instruments. Despite their prototype maturity and validation limitations, the systems show that information-centred design can reduce complexity and cost while preserving the required measurements, providing a basis for scalable neural interfaces and more accessible cardiovascular monitoring.