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Vibration Characterization of Gamepad Haptic Actuators: A Multi-Axis Measurement Approach with Spectral and Thermal Investigation

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Abstract **– This paper presents an extended investigation building upon a previously established compact multi-axis vibration measurement platform for the characterization of haptic actuators in consumer gamepad controllers. The system employs three MPU-6500 MEMS accelerometers interfaced to a RP2040 microcontroller via SPI, enabling synchronized tri-axial acceleration acquisition at up to 2 kHz across three spatially distributed measurement points. The platform was previously validated on controllers employing both eccentric rotating mass and voice coil actuator technologies, confirming clear differentiation of vibration profiles and the utility of RMS magnitude as an orientation-independent characterization metric. The present work extends this foundation in two directions: an investigation of thermal hysteresis effects in ERM-based controllers under sustained motor loading, and frequency-domain analysis of the acquired vibration signals using a custom Python-based spectral analysis tool supporting both automatic and manual window selection for DFT computation. Results of the thermal investigation are discussed alongside planned instrumentation improvements, while spectral analysis findings and tool capabilities are presented as a basis for further haptic feedback quantification.**

Keywords – Vibration Measurement, Accelerometer, Haptic Feedback, Gamepad Controller, Industry, Innovation and Infrastructure

I. INTRODUCTION

Haptic feedback has become a standard feature of consumer gaming peripherals, providing a tactile communication channel that complements visual and auditory outputs. Despite its widespread deployment, the physical vibration profiles produced by gamepad actuators remain insufficiently characterized in quantitative terms, and objective, repeatable measurement is a prerequisite for correlating haptic signal structure with user experience and for enabling principled actuator selection and design.

This work presents an extension of previously established research involving a compact multi-axis vibration measurement platform intended for characterization of gamepad haptic systems. Earlier development stages demonstrated the feasibility of simultaneous multi-point vibration measurements on controllers employing both eccentric rotating mass (ERM) and voice-coil-based haptic actuators. Previous investigations confirmed that the measured vibration profiles exhibit clear spatial differentiation depending on actuator placement and excitation conditions, while the RMS-derived vibration magnitude provides a robust, orientation-independent metric for comparative analysis. The present work builds directly on this validated foundation, extending the scope of investigation to thermal operating conditions and frequency-domain characterization of the acquired signals.

II. RELATED RESULTS IN THE LITERATURE

Haptic feedback in gaming peripherals has been approached from a number of different angles in the existing literature. The perceptual and communicative dimensions of gamepad vibration have been explored in [1], where an structured typology of rumble as a medium of expression in gaming contexts is provided, though without quantifying the underlying physical actuator parameters. On the measurement side, [2] examines human exposure to vibration from video game controllers, however the results are reported in relative, comparison-based terms rather than absolute physical quantities, and certain methodological aspects are not fully specified, which limits repeatability and quantitative interpretation.

The sensor employed in the present platform (MPU family) has been comparatively evaluated against alternative low-cost accelerometers under random vibration inputs in [3], demonstrating superior inter-axis uniformity and smaller reading deviations, supporting its suitability for vibration characterization applications.

While alternative approaches exist, the combination of spatially distributed multi-axis sensing, controlled excitation, and absolute physical measurement adopted in this work provide a repeatable and hardware-accessible foundation for thorough, quantitative measurement.

III. DESCRIPTION OF THE METHOD

A. System implementation

The measurement platform is built around a Raspberry Pi Pico board (RP2040 dual-core Arm Cortex-M0+, 133 MHz, 264 kB SRAM) interfacing three MPU-6500 three-axis inertial measurement units via a shared SPI bus. The three sensors are mounted at the left grip, the right grip, and the central chassis of the gamepad, enabling spatially resolved simultaneous measurement of vibrations generated by each actuator as well as their coupled propagation through the controller body. Physical attachment uses elastic bands rather than rigid adhesive fixings, minimizing mechanical damping (Fig. 1).

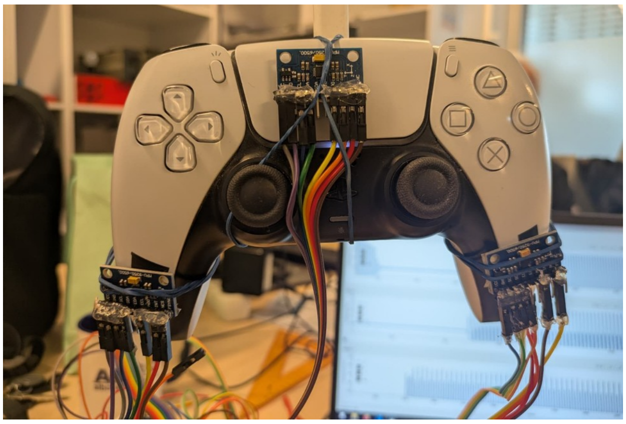

Fig. 1. Sensor placement and hardware configuration of the gamepad measurement system.

The MPU-6500 integrates a MEMS capacitive accelerometer with a 16-bit ADC providing simultaneous sampling across all three axes, configured to a ±4 g measurement range, selected experimentally to preserve full dynamic range while avoiding register overflow at actuator saturation. Alongside its accelerometric function, the MPU-6500 incorporates an on-die temperature sensor, which was utilized in this work to monitor ambient thermal conditions at each sensor location throughout the acquisition process.

The firmware for the original prototype was initially implemented in MicroPython, which proved insufficient for deterministic acquisition due to interpreter scheduling overhead. The implementation was migrated to C using the RP2040 SDK, achieving a sustained 2 kHz sampling rate with deterministic interrupt-driven timing, a rate motivated by the Nyquist criterion applied to the harmonic content of the actuator types under investigation.

B. Controller excitation and measurement configuration

Controlled haptic stimuli are delivered via a custom Unity editor tool [4], enabling definition of time-varying motor speed profiles with independent intensity control per actuator and configurable stimulus duration, compatible with both Xbox and Sony DualSense controllers.

Measurements are conducted with the controller in a free-hanging suspended configuration, ensuring mechanical isolation from external surfaces. A static bias calibration is performed at startup by averaging 50 samples per axis per sensor, with element-wise subtraction applied to all subsequent samples, removing both gravity projection due to imperfect sensor orientation and any static zero-g offset.

IV. RESULTS AND DISCUSSIONS

Example of a single signal measurement is given in Fig. 2. Measurement shown was taken with both VCA motors active simultaneously on a Sony PlayStation DualSense controller, driven by a linearly increasing amplitude command.

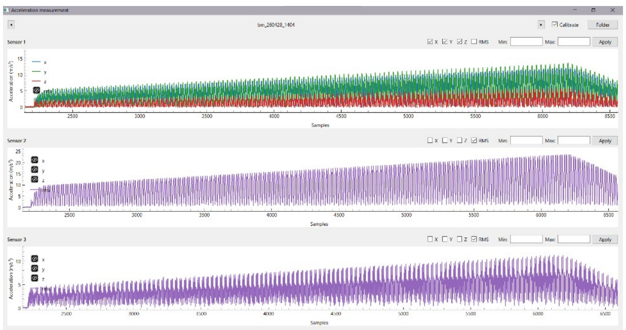

Fig. 2. Dual-Motor Linearly Ramped Vibration Response of a Sony PlayStation Controller

A. Signal post-processing and feature extraction

Dominant frequency and amplitude were extracted from the accelerometer measurements using a custom Python-based analysis tool. For each trial, the stationary portion of the signal was identified and isolated, excluding the motor ramp-up and decay transients. The tool supports both automatic and manual selection of the signal window used for DFT calculation, with an option for direct mutual comparison of the results obtained by each approach, allowing assessment of the sensitivity of the extracted spectral features to the choice of analysis window. The Discrete Fourier Transform was then applied to the isolated window to obtain the frequency spectrum, from which the dominant frequency was identified as the highest magnitude spectral peak, excluding low-frequency components attributed to rigid body motion and sensor drift. The amplitude was characterized as both the root mean square (RMS) and the peak value of the windowed signal.

B. Thermal hysteresis analysis

The thermal investigation yielded results that were inconclusive with respect to the presence of a measurable hysteresis effect in the vibration output of the ERM - equipped controllers. The temperature sensor available on the MPU-6500 measures the ambient temperature in the vicinity of the sensor mounting point and does not provide insight into thermal conditions inside the controller casing. Its role in this context is limited to ensuring measurement repeatability across sessions. Thermal loading of the actuators was achieved by running the motors continuously for a prolonged period, producing a noticeable temperature rise in the controller body perceptible by touch, consistent with the expected self-heating behavior of brushed DC motors under sustained operation. Measurements were then repeated during the cooling phase and compared against the pre-heating baseline.

Without a direct quantitative reading of the motor temperature, the relationship between thermal state and vibration output could not be precisely parametrized, and the observed changes in vibration amplitude and RMS magnitude did not exhibit a consistent or statistically separable pattern within the conditions tested. As a planned extension of this work, the controller casing will be opened and a dedicated temperature sensor placed in direct proximity to the motor, enabling quantitative tracking of actuator temperature during heating and cooling cycles and allowing the thermal loading protocol to be adjusted and better controlled accordingly.

V. CONCLUSIONS AND OUTLOOK

This work presented an extension of a previously validated multi-axis vibration measurement platform applied to the characterization of haptic actuators in consumer gamepad controllers. The system demonstrated reliable signal acquisition across actuator types, and the developed post-processing tooling enabled structured spectral feature extraction from the collected signals. The thermal investigation, while inconclusive in its current form, identified clear methodological directions for improvement. Spectral analysis of the acquired vibration data remains an active area of development, with ongoing work aimed at broadening the range of tested controllers and excitation conditions. The platform continues to be developed as a general-purpose, low-cost instrumentation solution with applicability extending beyond gaming peripherals toward broader vibration characterization tasks.

VI. ACKNOWLEDGMENTS

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