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Building a power meter for cycling

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Abstract

The main goal of this research was to design and implement a simple power meter for cycling. The designed power meter had to be affordable, so we chose to use the crank arm solution. In order to achieve the objectives, we had to measure the tangential force applied on the crank arm using tensometric stamps. Also, we had to measure the cadence based on zero-crossing of the applied force, and to transmit data to external applications using Bluetooth Low Energy (BLE). The hardware implementation is based on BF350-3AA tensometric stamps, HX711 amplifier and Seeed XIAO nRF52840 Sense microcontroller, while the software implementation is based on the HX711_MP.h and bluefruit.h libraries. Experiments prove that the proposed solution (cost approx. 29€) meets the requirements. After calibration, our system achieved a deviation of ~10% compared to Tacx virtual power data, confirming its feasibility for amateur training applications.

Keywords: power meter, cycling, tensometric stamps, crank arm, force, cadence

1 Introduction. The importance of measuring the power

Modern cycling, whether recreational or competitive, has benefited in recent years from advanced technologies, such as power meters, which measure the power generated by the cyclist, providing essential data for optimizing performance. These tools provide objective data on effort, helping cyclists optimize their training and compete more effectively, but their high costs often make them inaccessible to amateurs. This paper explores the development of an affordable power meter, designed to bring the benefits of this technology to a wider audience, without claiming the accuracy of top-of-the-line commercial devices.

The objectives of this research include:

- Designing a simple power meter prototype, using affordable components to measure power and cadence.
- Implementing a hardware and software system to process and transmit data via Bluetooth Low Energy (BLE) to external applications.
- Testing the prototype (on a trainer), comparing the data with the virtual power values provided by the manufacturer (TACX), to evaluate the functionality.

2 State-of-the-art in power meters for cycling

Since the 2000s, the power meter market has diversified with the emergence of new technological solutions that have reduced costs and simplified installation [1]. In 2006, PowerTap introduced a power meter integrated into the rear wheel hub. In 2012, Stages Cycling launched a single-sided power meter, mounted on the crank arm. The 2010s brought significant advances in portability and accuracy, with the launch of pedal-based power meters, such as the Garmin Vector (2013) and Favero Assioma (2017) [2]. Additionally, the integration of wireless protocols, such as ANT+ and Bluetooth Low Energy, has facilitated connectivity with bike computers and virtual cycling applications [3], [4].

Commercial power meters are classified by the location of the sensors used to measure power, with each type having specific advantages and limitations in terms of accuracy, portability, and bicycle compatibility [1]. The main categories include systems mounted on the bottom bracket, in the pedals, in the rear wheel hub, and other solutions such as in the gear or optical sensors, each tailored to different needs and budgets [5].

Crank-arm-mounted power meters, such as Stages and SRM, measure power by detecting the force applied to the crank using tensometric stamp sensors [6]. Advantages of these systems include compatibility with most bicycles and durability, but disadvantages include high costs for bilateral models and possible errors with unilateral systems. [5]. These power meters are popular both in professional cycling, due to their accuracy, and in the amateur segment, due to the affordability of models like Stages [6].

Pedal-mounted power meters, such as the Favero Assioma, Garmin Vector, and PowerTap P1, are popular for their portability and ease of installation, allowing for quick transfer between bikes. Advantages include portability and the ability to analyze pedaling asymmetries, but disadvantages include relatively high cost ($500–1000) and vulnerability of the pedals to wear or impact. [5].

Hub-mounted power meters, such as the PowerTap, measure power after chain and drivetrain losses, resulting in readings that are 5–10 W lower than those obtained at the pedals or gears [7]. Advantages include moderate cost (around $500) and reliability in a variety of conditions, but disadvantages include lack of portability (the hub is wheel-specific) and underestimation of power due to drivetrain losses. [5].

In addition to the main categories, there are gear-mounted (spider-based) power meters, such as Quarq and Rotor INpower, which measure power at the chainring level, offering accuracy comparable to SRM (±1÷2%) and compatibility with various bicycles. Other solutions include optical sensors, such as Ergomo, which use monoblock deformation to estimate power, but were abandoned due to high errors (over 5%) [8]. Systems based on "opposing forces", such as PowerPod, measure aerodynamic drag, slope and speed to infer power, without requiring sensors on the bike (error 5÷10%) [9]. Other experimental technologies, such as tire pressure sensors (TPS), are in development, but have not yet reached a commercial version [10].

The accuracy, precision, and efficiency of commercial power meters vary depending on the technology and usage [1]. Accuracy reflects the closeness to the true value of

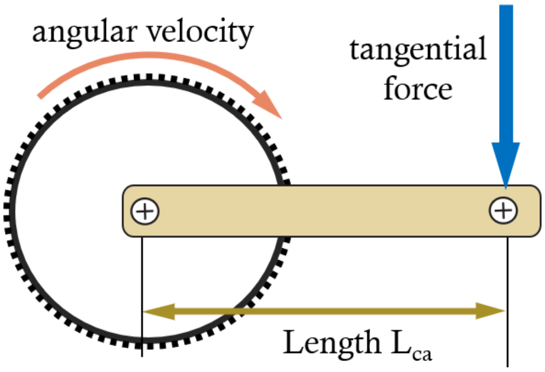

Figure 1. Force applied on the crank arm

power, precision indicates the consistency of measurements, and efficiency refers to the reliability of data with minimal energy consumption and reduced maintenance [5].

Comparative studies evaluate power meters against the SRM standard (±1-2% accuracy), and indicate significant variability among commercial power meters, from accuracy of ±1-2% to ±5-10% [11], [7], [9]. Maier et al. tested 54 units, reporting a mean deviation of -0.9% (standard deviation ±3.2%), but with some models deviating by more than ±5% [11]. Kirkland et al. determined that the contribution of work from each leg was 48.89% from the left leg and 51.11% from the right leg [8].

Efficiency varies depending on portability, battery and maintenance, with pedal-powered systems being the most versatile. Cyclists should perform regular calibrations and choose a model that suits their needs (e.g. bilateral for precision, unilateral for budget).

3 Theoretical basis for power meter on crank arm

The instantaneous power generated by a cyclist pressing on a crank arm (Fig. 1) is given by

$$P_{inst} = \tau * \omega \quad (1)$$

where P_{inst} represents the instantaneous power, τ the torque and ω the angular velocity. Further we have

$$\tau = F_T * L_{ca} \quad (2)$$

where F_T represents the tangential force (the only force component that develops power) and L_{ca} the length of the crank arm.

Instead of using ω it is more common to rely on the cadence RPM (Rotations Per Minute), so we have

$$\omega = RPM * \frac{2*\pi}{60} \quad (3)$$

The instantaneous power becomes

$$P_{inst} = F_T * L_{ca} * RPM * \frac{2*\pi}{60} \quad (4)$$

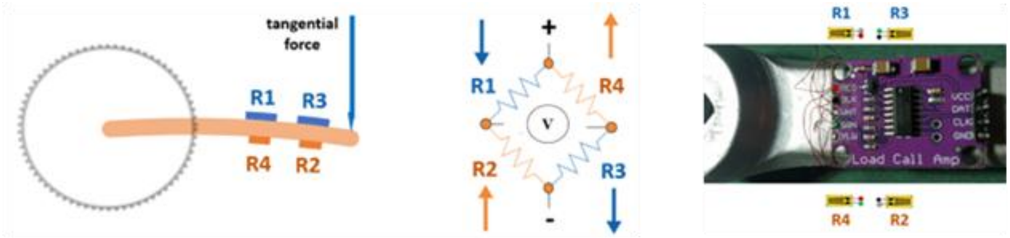

Figure 2. Arrangement of tensometric stamps in a complete Wheatstone bridge

When (as usual) we are interested in the average power we must consider the average tangential force. To maintain the hardware implementation as simple and cheap as possible, we will measure the force only on a single crank arm (as described later), then double the result (to factor in both pedals). In our case L_{ca} = 0.170 m.

4 Design of the power meter

The project aimed to create an accessible solution for real-time measurement of power and cadence in cycling, intended mainly for amateur cyclists. The system measures the force applied to the left crank arm and calculates the generated power, estimating the total value by doubling the contribution of the left leg. Data is transmitted wirelessly via Bluetooth Low Energy [4], complying with the Cycling Power Service standard [12] for direct compatibility with virtual cycling applications and existing cycling computers. The main goal was to experiment and test the feasibility of a functional and significantly cheaper alternative to commercial power meters, without claiming professional-level accuracy.

4.1 Crank arm with Wheatstone bridge

The approach of installing sensors on the left crank arm aims to directly measure the elastic deformation associated with the tangential component of the pedaling force, the only one responsible for generating useful torque. The mechanical configuration uses four resistive tensometric stamps arranged in a complete Wheatstone bridge, oriented "in an X" on the upper and lower faces of the arm. This arrangement, shown in Fig. 2, maximizes bending sensitivity, reduces temperature effects by exposing all stamps similarly, and increases the signal-to-noise ratio required for robust detection of useful force.

In this architecture R1 and R3 are positioned on the upper surface, and R2 and R4 on the lower one, so that the tension and compression generated by bending produce opposite resistance variations and, therefore, double the output of the bridge, simultaneously compensating for thermal influences and lateral forces. When the pedal is pressed, the upper surface stretches (R1 and R3 resistance values decrease) and the lower surface compresses (R2 and R4 resistance values increase), all four tensometric stamps contributing to the differential signal.

The integration of tensometric stamps on the crank arm requires careful surface preparation, precise alignments with the main stress directions, as various factors (such as orientation errors or uneven adhesive thickness) can induce parasitic sensitivity and

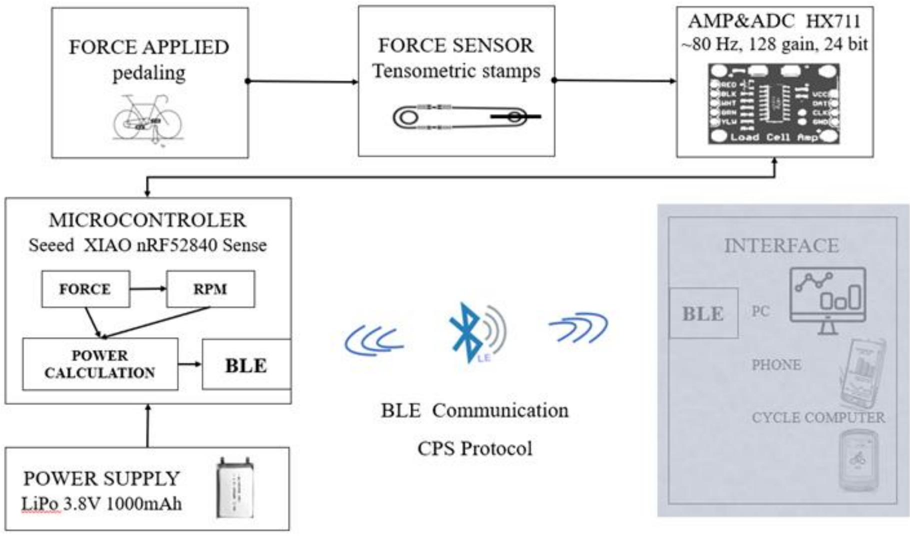

Figure 3. Block diagram of the designed system

drift. Choosing unilateral mounting (left crank arm) simplifies integration and costs, accepting that total power can be estimated by doubling the measured value, assuming approximately symmetrical pedaling. In practice, deviations from symmetry can introduce systematic errors, an aspect to be considered in calibration and data interpretation [5].

4.2 Hardware design

The measurement process is a classic for low-level force applications: a Wheatstone bridge with four tensometric stamps feeds an HX711 analog-to-digital amplifier/converter, whose data is processed by the Seeed Studio XIAO BLE nRF52840 Sense microcontroller and transmitted via BLE using the Cycling Power Service protocol. The block diagram of the designed system (Fig. 3) clearly illustrates the flow: force application → arm deformation → resistance variation in the bridge → amplification and sampling → processing and filtering → cadence/power calculation → CPS packaging and BLE transmission.

The HX711 provides 24-bit resolution, 128 programmable gain, and a sample rate configured at 80 SPS (SamplePerSecond). This rate is adequate for profiling force per rotation even at 180 RPM, when ~26 acquisitions per rotation are made (one reading at ~13.5°). Communication between the HX711 and the nRF52840 is performed through a two-wire serial interface (DAT and CLK), using a proprietary serial protocol implemented through bit-banging: the microcontroller generates the clock pulses, respecting the minimum setup and hold times (0.1 μs), and reading is triggered when the DAT pin transitions to LOW, signaling the availability of data. For robustness, the HX711 module is mounted on the inside of the crank arm, close to the axle, reducing the length of wires to the tensometric stamps and susceptibility to interference.

The XIAO BLE nRF52840 Sense central unit provides stable 3.3 V power supply (for HX711), has appropriate pinout for interfacing with HX711 (D2–CLK, D3–DAT) and includes an RGB LED for signaling statuses (initialization, BLE connection, errors). The platform was also chosen for its balanced combination of size, performance and superior energy efficiency compared to ESP32-based alternatives, with sleep

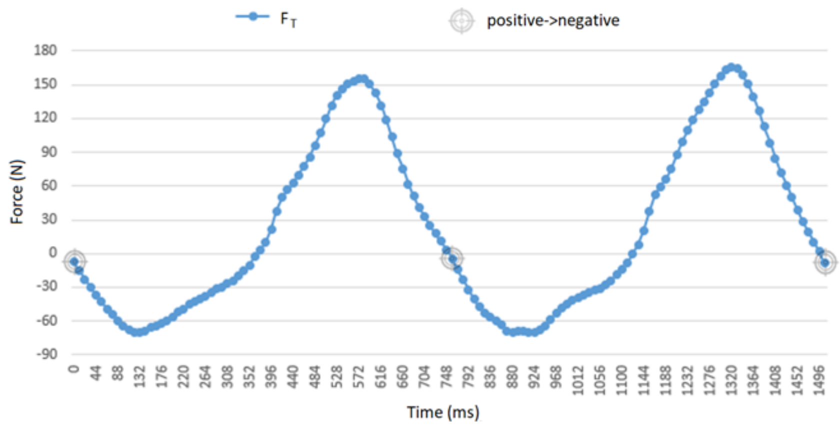

Figure 4. The force applied within an interval of two complete revolutions

consumption dropping below 2 µA, compared to ~43 µA (ESP32-C3) and ~15 µA (ESP32-C6), thus supporting portable applications with extended autonomy.

The system is powered by a 523450 LiPo battery with a capacity of 1000 mAh and a nominal voltage of 3.7 V, enough for approximately 10 hours of continuous use.

4.3 Measuring force and cadence

The acquisition of raw values from the HX711 is synchronized on the interrupt, when the DAT pin goes LOW. The conversion into physical force is achieved through a two-step calibration: offset compensation (zeroing) and application of an experimentally determined scaling factor. Following the tests, using the calibration method with the application of predefined forces, a scaling factor of 0.000165 N/unit was established. This conversion is paramount for subsequent torque and power calculations.

Cadence is determined by detecting zero-crossings of the calibrated force during rotation, using a hysteresis to avoid false triggering induced by noise and vibration. Threshold filters for RPM (realistic range 10 to 200 RPM) and power (10 to 400 W) eliminate noise and false rotations caused by oscillation at low speeds. Fig. 4 provides visual context for the signal dynamics and marking of rotation events used in the cadence calculation, illustrating the effect of filtering on consistent detection of zero crossings.

4.4 Software design

The software architecture is modular and mirrors a clear flow: initialization of subsystems (HX711, BLE, GPIO, LED), configuration of interrupts for data acquisition, main loop for signal processing (offset, scaling, filtering), detection of rotation events and calculation of cadence/power, followed by packaging and publishing of data via BLE. The libraries used include HX711_MP.h [13] for interfacing with the HX711 load cell amplifier and bluefruit.h [14] for the BLE stack. BLE callbacks handle connection/disconnection events, initialize services/features, and trigger notifications when new valid results occur. Thanks to the applied "publish-on-event" strategy, data is transmitted only when a complete rotation is detected, optimizing energy consumption and avoiding unnecessary traffic.

4.5 BLE protocol frame

Data transmission is done over Bluetooth Low Energy, using Cycling Power Service (CPS), a standardized GATT service for devices that measure cycling power. The BLE architecture involves the application-level GAP/GATT layers, the Attribute Protocol, and the L2CAP/HCI interfaces, which interact with the radio Link Layer; this structure ensures interoperability with cycle computers and software platforms [15]. Data is delivered via the Cycling Power Measurement feature (UUID: 0x2A63), configured with the notification property. The data frame has a fixed length of 8 bytes and is transmitted in little-endian format. The first two bytes represent the flags field; in the current implementation, the value 0x0020 is used, which sets bit 5 (Crank Revolution Data Present) and indicates the inclusion of crank revolution data. Bytes 2–3 contain the 16-bit signed instantaneous power (in watts), bytes 4–5 represent the total number of rotations, and bytes 6–7 encode the time of the last rotation event (in 1/1024s quanta). A complete example is shown in Table 1 for the following values; power = 251 W (0x00FB), total Crank Revs = 7 (0x0007), last Crank Event Time = 5120 (0x1400) and flags 0x0020.

Table 1 Creating a frame for BLE transfer

Octet	Value (Hex)	Description	
0	0x20	Flags (LSB)	0x0020
1	0x00	Flags (MSB)	
2	0xFB	Power (LSB)	251W
3	0x00	Power (MSB)	
4	0x07	Number of rotations (LSB)	7 rotations
5	0x00	Number of rotations (MSB)	
6	0x00	Event time (LSB)	5120 (=5 sec)
7	0x14	Event time (MSB)	

Notifications are only triggered when a full rotation has been detected and there is at least one active connection, and the blue LED is activated with each transmission for visual feedback. This implementation minimizes power consumption and ensures compliance with the CPS standard, thus facilitating interoperability with specific applications and devices.

4.6 Results

The prototype reached a sampling rate of 80 SPS, enough for capturing the force profile, thus at cadences of 180 RPM capturing ~26.7 samples per rotation. However, accuracy is influenced by the limited precision of the scaling factor and sensor drift, influenced by the adhesive used to attach the tensometric stamps, and by fluctuations in battery voltage. Initial dynamic tests revealed a discrepancy between the theoretically estimated power (100 W) and the values measured on the crank arm (60–70 W), a discrepancy attributed to the imprecision of the scaling factor. The tests were performed using the Tacx Blue Motion trainer [16] and the Tacx Training app, which estimates power based on speed and the known power curve for a given resistance level (100 W corresponding to 15.7 km/h in level 4). Subsequent more rigorous recalibration improved the accuracy, ultimately reaching a deviation of ~10%.

The usefulness of the system, even if it does not reach the precision of professional systems and does not provide exact information about the power exerted by the cyclist, lies in its accessibility and the ability to provide real-time feedback in a format compatible with cycling devices and applications. Also, its consistent use in training provides amateur cyclists with a reproducible power metric over time, which allows for consistent monitoring of progress and comparison of training sessions, offering an excellent cost-benefit ratio.

5 Conclusions and future work

The development of a power meter involved the integration of hardware and software components in a dynamic environment, with additional requirements for cost, precision and robustness. The lack of specialized equipment, the variable quality of components, and the complex nature of cycling power measurement have generated significant challenges, both hardware and software.

The BF350-3AA stamps were attached to the crank arm with professional general-purpose adhesive, selected for its adhesion to metal surfaces. However, the adhesive exhibited slow elastic recovery at high loads, which influenced the stability of the readings.

Integrating the HX711 library with BLE communication was problematic. The standard HX711 library (Bogde) worked correctly in individual tests, but when combined with the BLE stack (bluefruit.h), the code stopped running, with no obvious compilation errors.

The HX711_MP.h library was adopted as a solution, but it exhibited sporadic resets at 10 SPS and frequent resets at 80 SPS, caused by overlapping HX711 interrupts with BLE radio activity. Changes to the library included reducing the interrupt blocking period (from a block for the entire loop to a block for a single instruction in the loop body), thus preventing the HX711 from entering "power-down" mode and resetting the microcontroller.

Table 2 Cost of the designed system

Component	Approx. Price (€)	Total cost (€)
Seeed XIAO	18	29
Battery 523450 LiPo	8	
HX711	2	
BF350-3AA stamps (all)	1	

Real-time testing and debugging were hampered by the inability to use the serial monitor while pedaling. The use of the BleUART protocol and BLE applications (e.g. nRF Connect, Bluefruit Connect) for debugging introduced a latency of ~200 ms per transmission, affecting real-time data acquisition.

The prototype, based on the Seeed XIAO nRF52840 Sense microcontroller, HX711 amplifier and BF350-3AA tensometric stamps, proved the feasibility of a DIY alternative to commercial power meters, offering promising results despite the technical challenges. A major advantage of the prototype is its significantly lower cost compared to commercial power meters, such as SRM or PowerTap, which cost hundreds or thousands of euros. The use of affordable components, with a total cost of ~29€ as detailed in Table 2, and open-source software (Arduino IDE, HX711_MP.h and bluefruit.h libraries) makes the prototype attractive for amateur cyclists. The prototype, being much cheaper, can be easily multiplied, without the need for transfer when one owns multiple bikes.

Certainly, to improve the performance and reliability of the power meter, other developments should be considered in future, such as:

- Using a specialized adhesive and better quality tensometric stamps to minimize the observed springback, adding a second set of stamps on the second crank arm.
- Design of a robust, weatherproof housing (e.g. IP65 standard), to protect the components (HX711, microcontroller, battery) against dust, moisture and vibrations during pedaling. Possibly using a modular design, with a fixed part (the tensometric stamps and HX711, mounted on the crank arm) and a portable part (the microcontroller and battery), connected by a quick coupling system (e.g. magnetic connectors or pins).
- Implementing a microcontroller "deep sleep" mode during periods of inactivity and adding battery status monitoring and notification via BLE.
- Comparison of the prototype with a commercial reference power meter (e.g. SRM) under controlled conditions, to adjust the scaling factor and increase and validate the accuracy.

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