This full text paper was peer-reviewed at the direction of IEEE Instrumentation and Measurement Society prior to the acceptance and publication

Ride Profiling for a Single Speed Bicycle Using an Inertial Sensor

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***Abstract*— Quantifying aspects related to riding helps cyclists keep track of their performance. Being able to track performance enables a greater understanding of athleticism, strength and endurance required to work on areas of potential improvement. The technology solutions currently available on-the-field facilitate real-time monitoring of these determinants. These solutions render accurate measurements of primary parameters such as cycling speed, cadence and pedal force. However, there is a lack of compact and integrated solutions to quantify the effect of external factors like terrain and slope. Integration of these features along with the measurement of primary parameters enables a comprehensive understanding of ride behaviour and handling. This paper presents a system to quantify these diverse aspects for a single speed bicycle using a single inertial sensor device. Computations on measurements are done on the device and results are transmitted wirelessly to a smartphone. The device is attached to the rear wheel, and it measures primary parameters such as cycling speed and cadence. Relative pedal force, acceleration and braking metrics are derived from the variations caused in the speed profile computed. Terrain and slope affect these derived parameters, and therefore the changes caused by them are measured to obtain relativistic information on the effect of these external factors. Real-time visualization of primary aspects and long term monitoring of performance under the influence of varying external factors benefit cyclists with insights for training and improvement.**

Keywords—sports technology, cycling sensor, inertial sensors, athletic performance

I. Introduction

Cycling has gained significant popularity over the last few decades, and a significant number of people begin pursuing this competitive sport every year. The number of cyclists in the U.S. has risen from 43 million to 47.5 million in 2017 over the past three years [1]. In a bid to uphold the competitive spirit, cyclists are continually looking for ways to gain valuable insights into their abilities and to strengthen their techniques. The lack of assisted training limits access to such insights, eventually stunting the improvement. Ultimately, the athlete's potential to perform better is left unexplored. As a sport that limits the continuous presence of a trainer while performing, cycling needs a real-time monitoring solution to keep the athlete apprised on the go. However, technology solutions are slowly proliferating the sports segment to help cyclists achieve this quest.

Primary aspects such as cadence, cycling speed, and the pedal force are monitored by these solutions to gauge performance. Cadence, or the number of pedal rotations in a minute, indicates the ability of the cyclist to move their limbs faster. This rate indicates the efficiency of a cyclist as it signifies the amount of effort required to travel at a given speed. Pedal force is a direct measure of the effort applied on the pedals to propel forward and sustain the speed. The magnitude of power that can be delivered through the legs is measured by this metric. Cycling speed is the determining factor for assessing racing performance. Furthermore, it a sign of an athlete's overall fitness levels. The ability to maintain higher speeds is an indicator of the endurance possessed by the athlete.

Riding skills are assessed by secondary parameters that include strategies to accelerate after slowing down for pits or pedestrian crossings. This is achieved through observing the acceleration profile that contains bicycle forward propulsion and braking patterns. In addition, acceleration profile suggests cues about the athlete's explosiveness to impart momentum and propel forward [2]. External factors such as slope and terrain affect the kinematics involved herein and therefore, need consideration during the interpretation of the aforementioned aspects. The inclusion of such factors improves the overall understanding of ride behaviour, ride handling strategies and performance characteristics associated with the cyclist.

Contemporary technology that enables the exploration of these primary aspects include both laboratory-based setups and on-the-field equipment. Laboratory-based services by bikefitting.com [3] render an accurate and detailed visualisation of the pedal force and the asymmetry associated with it. On-the-field solutions like speed and cadence monitors by Polar Electro [4] can be attached to the bicycle to provide real-time cycling speed and cadence. Pedal force and power applied on pedalling can be measured using attachable accessories such as Garmin Vector 2s by Garmin Ltd. [5]. Extensive research work on developing portable measurement modalities has been done to obtain parameters offered by laboratory settings. Research [6] demonstrates the ability of inertial sensors to measure bicycle kinematics and rider's movements. Wheel speed and forces such as brake force, saddle force and handlebar force in an off-road bicycle are measured using an instrumented bike in [7].

Measurement techniques involving modification of bicycles are not suitable for standard riding scenarios. Solutions based on laboratory settings, despite assuring accuracy, are constrained to a capture volume thereby restricting monitoring of aspects that can be measured in an outdoor environment. Attachable devices are purpose-built, and therefore limited to monitoring only a few of the parameters involved. Several of these devices are required for an overall understanding of an athlete's performance, and moreover, integration of such devices is usually inconvenient. These devices are seldom used in the monitoring of the aspects of slope, terrain, or propulsion due to their diminished capabilities in terms of measurement hardware and processing power.

A novel system employing an inertial sensor to monitor several primary and secondary aspects associated with cycling

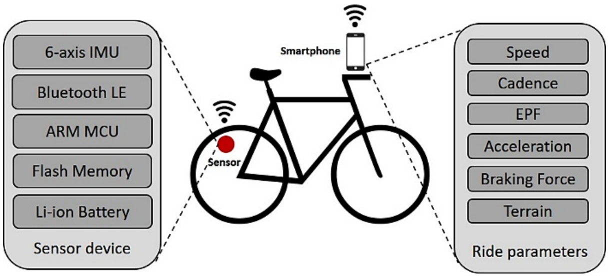
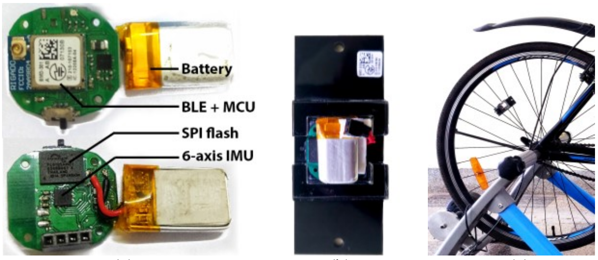


Fig. 1. System Architecture



(a) (b) (c)

Fig. 2. Hardware setup (a) Hardware used for measurement
(b) Enclosure assembly (c) Measurement device attached to rear wheel

is proposed in this work. This research is first-of-its-kind in exploring the capabilities of a single Inertial Measurement Unit (IMU) to quantify crucial aspects useful to a rider. The developed solution is a highly integrated embedded system that combines the functionalities of existing commercial solutions in a miniaturized form factor. This integration enables computation of secondary parameters, from multiple primary parameters measured by the system, which are not offered by existing solutions. The IMU is mounted on the rear wheel of a single speed bicycle with a known gear ratio to develop parameter estimation algorithms. Parameters such as cycling speed, cadence, relative pedal force, propulsion and braking, terrain and slope are obtained. Providing these parameters in an aggregated form enables the athlete to gain holistic insights on athletic performance and ride techniques. The design of hardware, implementation of algorithms and computation of various parameters are detailed in the upcoming sections of this paper.

II. System Design

The device primarily consists of a 6-axis digital IMU measuring tri-axial acceleration and tri-axial angular velocity through an integrated accelerometer and gyroscope. It can measure acceleration up to ±32 g (1 g = 9.8 m/s^2) with a sensitivity of 1024 LSB/g and angular velocities up to ±4000 degrees per second (°/s) with a sensitivity of 8.2 LSB/(°/s). Data acquired from the inertial sensor at the rate of 100 samples per second is processed on-board by an ARM Cortex M4F Micro Controller Unit (MCU). The MCU serves as a computing platform that runs algorithms optimised for a processor with limited capabilities, thereby enabling on-the-edge computing without depending upon on connected devices. However, the results of computation i.e. the measured parameters are transmitted to a smartphone or a dedicated display unit wirelessly through Bluetooth Low Energy (BLE). A 64 MB flash memory unit stores the measurements that can be later transferred to a computing device for long term analysis. Fig. 1 illustrates the overall architecture of the system being discussed.

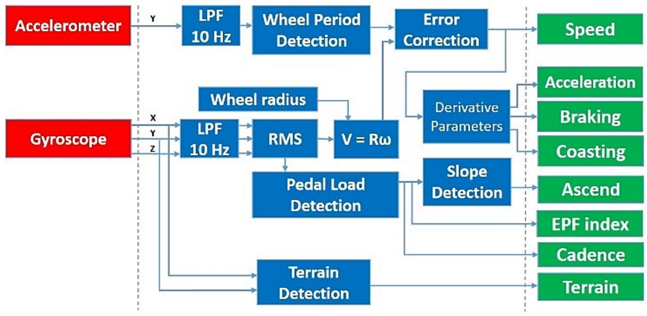


Fig. 3. Software overview illustrating various algorithmic modules to compute cycling parameters

A 100 mAh rechargeable battery is used to power the device for a minimum of 36 hours of continuous operation. The device having dimensions 19 x 21 x 8 mm (L x B x H) is depicted in Fig. 2(a). It is securely mounted within a rigid housing that has provisions for attaching it to the spokes of a bicycle wheel as seen in Fig. 2(b). Fig. 2(c) shows the measurement system attached to the rear wheel of a Cosmic Chase FS single speed hybrid bike upon which primary experiments were carried out. A secondary road bike, Giant SCR 1, was also used to carry out the experiments.

III. Profiling Parameters & Algorithms

Primary and secondary parameters help the athlete identify areas to improve upon, that would otherwise remain unexplored. Primary parameters such as cycling speed, cadence, and pedal force metrics require continuous monitoring to gather prompt insights while on track. These parameters, when augmented with secondary information about slope and terrain enable assessment of performance trends, endurance, and strength of the cyclist.

Algorithms to estimate these parameters were developed using MATLAB (Mathworks Inc.) and ported into the embedded hardware for real-time measurements. Raw data from the accelerometer and gyroscope were first processed using signal processing methods to isolate the pertinent information which is then selectively fed to software modules to obtain parameters. An overview of the modules indicating the flow of data is shown in Fig. 3. The logic involved in obtaining each of the parameters is discussed as follows.

A. *Signal Conditioning*

The vibration of the assembly during rides and irregularities on the surface of the road appear as motion artefacts in the accelerometer and gyroscope output in addition to noise. Since the maximum interested frequency is the rotational frequency of the wheel that cannot practically exceed a few tens of kilometres per hour, the rotational frequency of the wheel is limited to less than 10 Hz (7.57 Hz for a 700c wheel going at 60 km/h). A low pass filter with 10 Hz cut-off frequency is applied to the incoming accelerometer and gyroscope signals.

B. *Cycling Speed*

The requirement of maintaining high speeds is a prime marker of cycling as a sport, and it directly reflects upon the competitive spirit and capabilities of an athlete. Tracking the speed is vital for a cyclist to pace out long rides and assess the effect of external factors, such as aerodynamic drag (air resistance pushing against the rider's moving direction), and

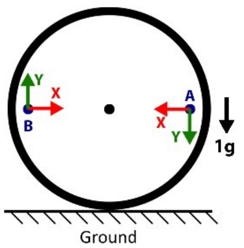


Fig. 4. Orientation of an accelerometer, attached to a wheel, at various points during wheel spin. Y-axis of the accelerometer measures +1g and -1g at points A and B, respectively

effect necessary adjustments. The cycling speed can be obtained from the IMU using two independent methods.

a) Angular Velocity Method: Anguar velocity of a spinning wheel, being the same for all points on the wheel, can be measured by a gyroscope attached to it. This is computed as the net angular velocity from all the 3 axes of the gyroscope in order to account for tilt inconsitencies in mounting. For a spinning wheel with net angular velocity ω, the speed of the bike obtained using angular velocity method V_g, during ideal riding conditions, is given by the equation,

$$V_g = R\omega \times 3.6 \quad \text{km/h} \qquad (1)$$

Where, R is the radius of the wheel measured as described in [8] or estimated using the ETRTO tire size.

This technique has been used in previous works [6] to obtain cycling speed from gyroscope. At a sampling rate of 100 Hz, this approach provides 100 speed measurements per second irrespective of the speed of the vehicle.

b) Wheel Period Detection Method: Accelerometer attached to the wheel measures acceleration acting at its point of attachment. Depending on the position of this point with respect to the center of the wheel, the acceleration on a spinning wheel can be the acceleration due to gravity or the centripetal acceleration directed towards the center of the wheel or both.

In the case of 2 points on the circumference of a stationary wheel as shown in Fig. 4, the accelerometer at point A experiences a downward force of 1g that acts along its positive y-axis, and at point B, 1g is exerted along its negative y-axis. This change between +1g and -1g is manifested as observable variations during wheel spin and is termed as the wheel spin pattern. The time taken for one rotation of the wheel, i.e. its period, is computed from this pattern. Fig. 5 illustrates detection of peak points in the wheel spin pattern from which timing information of the wheel spin is obtained.

Let T_s be the period of rotation of the wheel from which speed is to be computed. Under ideal riding conditions where the rotational motion is completely converted into translational motion, the forward speed obtained using the wheel period method V_a, is given by the equation,

$$V_a = \frac{2\pi R}{T_s} \times 3.6 \quad \text{km/h} \qquad (2)$$

Where, R is the radius of the wheel measured as described in [8] or estimated using the ETRTO tire size.

Variations in the temperature and gyroscope bias over riding sessions cause an error in the computed speed [9]. The proposed system employs an accelerometer to augment the gyroscopic measurements to account for inaccuracies. An error correction logic compares the speed computed using both the methods. Deviation in gyroscope computed speed from that of the accelerometer based method over time indicates a drift in gyroscope bias. This relative measure of gyroscope bias controls the correction involved gyroscope computed speed to obtain reliable speed measurements.

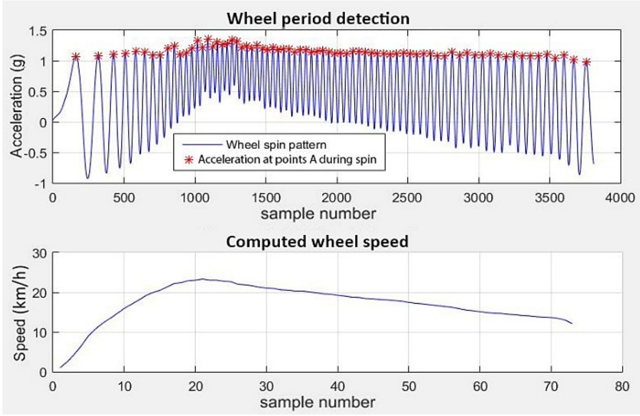


Fig. 5. Cycling speed calculation using accelerometer. Wheel spin pattern is the acceleration observed along accelerometer y-axis. * corresponds to acceleration values when the attached sensor crosses point A. Period of rotation is the time between two adjacent * markers.

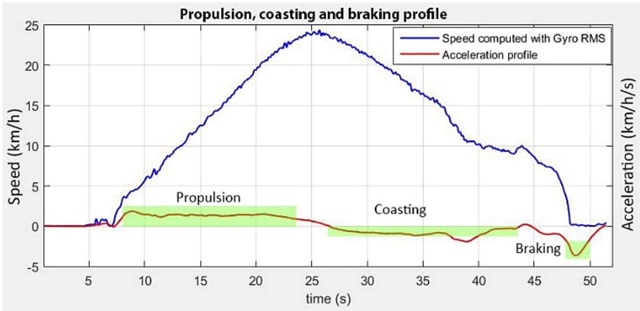


Fig. 6. Detection of propulsion, coasting and braking from derivative of speed obtained by gyroscope RMS method. A consistent high value beyond a threshold (1 km/hr/s) indicates propulsion. Coasting is signified by negative values of acceleration above a threshold (-1 km/hr/s) fixed for braking.

C. *Acceleration & Braking*

Sprint racing requires explosive power to attain maximum speeds in a short burst of time. This ability to convert strength into speed in a fleeting phase (impulsive strength) allows for movements beyond those offered by raw strength. Explosive power is necessary to regain speeds after stopping or slowing down in the course of the ride. The measured acceleration represents this explosive power possessed by the athlete. Braking profile provides hints regarding the rider's attention and serves as an indirect indicator of the load taken on the neck and shoulder joints. This knowledge, when combined with information about harsh terrains, helps deduce the causes of shoulder pain and injuries.

The derivative of cycling speed indicates speed variations over time that is used to infer acceleration and deceleration patterns. An algorithm detects the polarity of these speed variations to classify between propulsion, coasting and braking. A consistent increase in the speed beyond a predefined duration threshold outputs a positive slope that is detected as propulsion — riding on a flat surface with idling pedals result in a gradual decrease in speed that is classified as coasting. A drop in the speed beyond a rate threshold indicates braking. For all the three detected categories, the algorithm outputs the acceleration/deceleration as a change in speed (km/h) per second. Empirical methods obtain the threshold parameters for various cases through data collected from cyclists and bicycles. Fig. 6 illustrates the profiles of conventional propulsion, braking, and coasting as obtained from speed measurement. The simplified version of the algorithm is mathematically represented by equation (3).

$$\alpha_m = \frac{dV_g}{dt} \tag{3.1}$$

$$\alpha_p = \begin{cases} propulsion; & \alpha_m > \alpha_{th}^p \\ coasting; & \alpha_m < 0, \alpha_m > \alpha_{th}^c \\ braking; & \alpha_m < \alpha_{th}^b \end{cases} \tag{3.2}$$

Where, α_m is the computed acceleration, α_p is the acceleration profile and α_{th}^p, α_{th}^c and α_{th}^b are the threshold parameters for detection of propulsion, coasting and braking, respectively.

D. *Pedal Force Exertion*

Power applied on the pedals in order to propel the vehicle forward is linked to the pedal force applied. The potential to exert more power in order to accelerate is measured by exerted pedal force. While propulsion relates to the explosive power of the athlete, pedal force represents the strength possessed by the individual. Monitoring the improvements in pedal force along with the acceleration profile helps in understanding the strength of lower body muscles. The ability to accelerate depends on the magnitude of pedal force exerted and the repetitions associated with it.

Application of pedal force imparts momentum to propel the bicycle forward and pedalling is modulated as incremental variations in speed. This variation is called Pedalling Pattern (PP) and is characterized by points of maximum and minimum pedal force exertion. Fig. 7 shows the PP captured from speed profile and computation of parameters associated with it. The amplitude of PP is a relative indicator of pedal force applied and is termed as Exerted Pedal Force (EPF) index. EPF index is scaled between 0 and 1, where 1 corresponds to the pedal force exerted while propelling the bicycle (of a known gear ratio) from rest. EPF index of 0 corresponds to the pedal force exerted when no significant pedalling (determined by a significance threshold) is involved while the vehicle is moving at higher speeds. The significance threshold is limited by movement artefacts captured by the measurement system and is determined through empirical methods.

If A_p is the amplitude of the PP, the EPF index is given by the equation,

$$EPF = \begin{cases} \frac{A_p}{A_{rest}}, & A_p > A_s \\ 0, & otherwise \end{cases} \tag{4}$$

Where, A_s is the significance threshold for reliable detection of a PP and A_{rest} is amplitude of PP when starting from rest. This amplitude is subjective to the rider and therefore it is automatically updated during the start of a ride session.

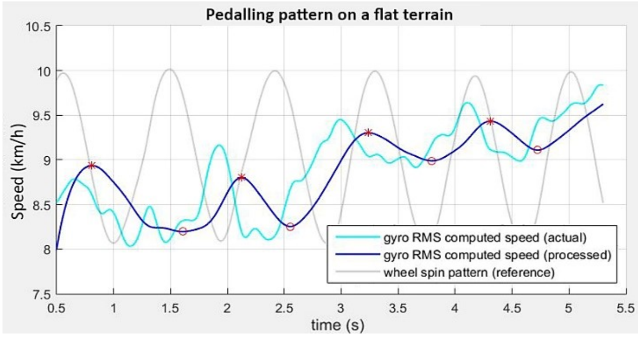


Fig. 7. Pedalling pattern observed on gyroscope based speed. Markers * and o indicate the maximum and minimum effort applied during each pedalling cycle, respectively. The magnitude difference between these pairs is the amplitude of the pedalling pattern and reduces as the vehicle speeds up. (Wheel spin pattern overlay is only for visual reference)

It is observed that, as the bicycle speeds up, the amplitude of the pedalling pattern diminishes. This phenomenon is associated with the freewheel mechanism and the fact that the bicycle gains linear momentum as it speeds up, thereby requiring less efforts on the pedal to propel the bicycle forward.

E. *Cadence*

Cadence is directly associated with the muscle fatigue experienced by the cyclist [10]. This measurement quantifies the pedalling rhythm that a rider maintains and can be used to categorize it as spinning (fast cadence) or mashing (slow cadence). The former involves usage of slow twitch muscle fibres whereas, the latter requires fast twitch muscle fibres. Finding an optimal cadence is subjective to the cyclist and continuous monitoring helps in identifying the physiologically efficient cadence for the rider.

Cycling cadence is estimated by an algorithm that extracts timing information between the peaks in the PP. This time is the duration for the pedal to make one full rotation. Cadence is computed when a prominent pedalling pattern is detected by the system. A significant EPF index (values greater than 0) indicates the existence of a pedalling pattern from which cadence can be computed.

If T_c is the period of rotation, the cadence computed from pedalling pattern N_c is given by the equation,

$$N_c = \frac{1}{T_c} \text{ x } 60 \quad \text{cycles/min} \tag{5}$$

F. *Slope index*

Quantified effects of external factors enable meaningful interpretation of primary aspects. It is necessary for a rider to consider slope during the assessment of muscle strength and explosive power. Slope significantly affects cadence and speed measurements and therefore inclusion of slope as a metric is crucial. Moreover, inclusion of metrics for slope helps assess athletic performance with the external load applied.

Since slopes alter the efforts required by the rider, their effects are seen in the PP. These effects include sustained prominence of PP with no significant increase in the speed of the vehicle in case of an uphill slope. This indicates a continuous exertion of pedal force during an ascend to sustain the climb. For a downhill slope, the speed increases consistently with no prominent PP, when braking is not involved. Slope index is a relative and non-linear numerical

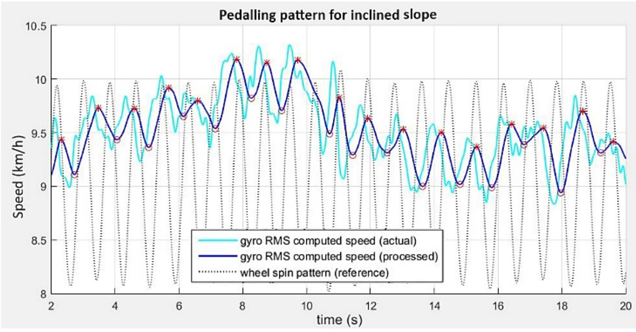


Fig. 8. Pedalling pattern for a ride on inclined slope. The amplitude of pedalling pattern, indicated by * and o markers, remains fairly consistent without significant increase in speed over a long duration. (Wheel spin pattern is for reference and does not represent actual values)

metric of the track's inclination and it is indirectly resolved using the acceleration profile and EPF index. Therefore, in terms of these parameters, a steeper uphill is signified by a small acceleration i.e. minimal increase in speed over time, as shown in Fig. 8, with a higher EPF index. Similarly, a steeper descend is characterized by high acceleration and a lower EPF index. Positive and negative values of slope index correspond to inclining and declining slopes respectively.

Assuming no braking is involved, the simplified logic for obtaining slope index for a surface, Δ_s is given as,

$$\Delta_s = \begin{cases} \frac{EPF}{\alpha_m}\alpha_i, & EPF > 0 \\ -\frac{\alpha_d}{\alpha_m}, & EPF = 0 \end{cases} \tag{6}$$

Where, α_m is the computed linear acceleration, α_i is the linear acceleration required to ascend a 50% slope (26.57°) with an EPF of 1 and α_d is the linear acceleration generated when descending down a 50% slope with no EPF.

G. Terrain Detection

A rugged terrain may cause physical discomfort and increase the chances of injury. As mentioned earlier, braking and terrain ruggedness can exert a load on the shoulder joints, especially bikes with flat handlebars. Since the strategies of ride handling and ride behaviours vary with the road surface, measuring terrain ruggedness is crucial in the process of determining injury risks in endurance riders.

Riding on a flat road causes notable variations in the angular velocity only along the primary axis i.e., the gyroscopic axis that is aligned to the axis of rotation. However, rugged terrain causes notable artefacts that are picked up by both the primary and secondary axes. A terrain detection algorithm is built around a model based on data collected from flat and rugged terrains. This algorithm takes input in the form of data from secondary axes of the gyroscope and outputs a binary result, indicating if the terrain is flat or rugged. Fig. 9 depicts a sample gyroscope axes data depicting the difference between the two types of terrains.

IV. Experimental Results & Discussion

Three cyclists evaluated the reliability of the algorithms under controlled and outdoor environments, and the accuracy of the insights provided was verified. The device connected to the smartphone displayed measurements in real time to the rider. The raw data, as well as the computed parameters, were also logged onto the device for offline verification. A professional trainer kit with variable slope configuration was used to emulate the cycling load.

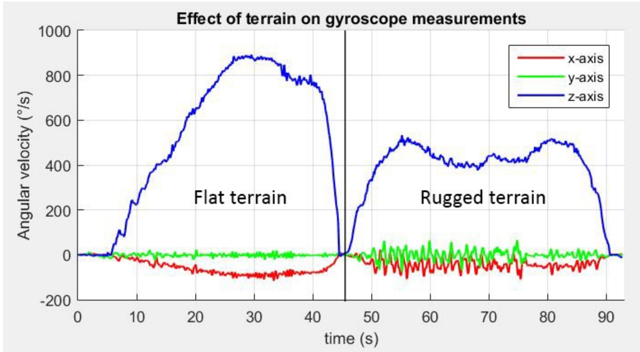


Fig. 9. Gyroscope data showing difference in recorded patterns during rides on flat and rugged terrains.

Cycling speed output was verified using an industrial grade contactless tachometer. The cycle was mounted upon a Cascade MagPlus trainer, and an electric motor assembly drove its rear wheel at a constant speed. The readings obtained from the optical tachometer and the proposed device were averaged over 10 seconds. This process repeated at various speeds, and the results of the experiment have been illustrated in Fig. 10.

Test rides were conducted on ramps and sloped terrains of increasing inclinations and increasing values of slope indices were estimated by the device. The slope indices output did not comply to a trend or a linear relation. However, the ability of the system to quantify incremental slopes was verified. Video recording with a helmet mounted camera was made for a ride consisting of rugged and flat roads. The system was able to detect terrains accurately as indicated through the reference video.

Cadence and EPF index measurements remain limited by the speed of the vehicle. At higher speeds the pedalling pattern is less prominent and overridden by artefacts that causes false measurements. Therefore, in order to suppress false output, a safe threshold is set above which cadence is not computed. Owing to this reason, an experiment conducted to verify slope for downhill rides with pedalling gave poor results. This indicates the inability of the algorithm to reliably detect pedalling patterns during descends. Braking during downhill rides aggravates the reliability of estimated output.

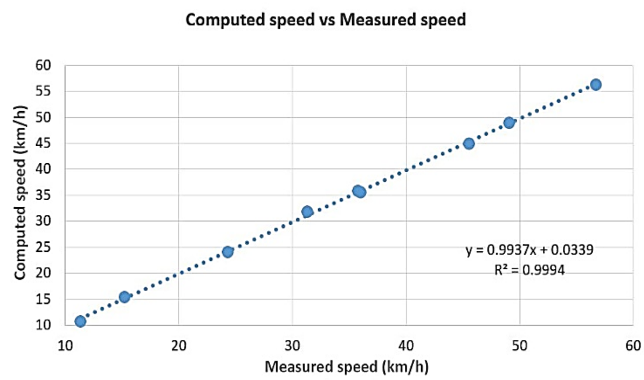


Fig. 10. Comparison of speed computed using the device and speed measured by a tachometer instrument in an indoor test setup.

The gear ratio for the bicycles used in the experiments was fixed and known. This made the computations required for measurements simpler. However, inclusion of methodologies to detect shifts in gear ratio and extension of the algorithms to apply appropriate scaling factors are to be done to transform this research work into a complete system.

V. CONCLUSION

This research investigated the ability of inertial sensors to measure multiple parameters relevant to cycling and a highly integrated embedded system using a single IMU was developed for measurement. Computation and estimation of these parameters were achieved through software algorithms implemented in miniaturized system. This integration and miniaturization is advantageous in obtaining parameters that are not offered by existing solutions. This single device measuring diverse parameters can be a convenient alternative for other commercial devices intended for ride assessment. In addition, quantified insights provided by the system prove to be effective in benchmarking performance of cyclists. Connecting these parameters can help in deducing high level aspects such as risks of injury and endurance levels. For example, the proportion of pedalling activity with respect to the ride duration on a given terrain can reflect the endurance levels of the rider. Similarly, with the knowledge of tracks, slopes and terrains, in addition to conventional parameters, skill levels of the cyclist can be determined and expressed numerically.

The scope of this work is to introduce the potential of inertial sensors to deliver meaningful insights for cyclists and techniques to obtain primary and secondary parameters were discussed in the paper. Further research is in progress to include learning-based models to augment parameter estimation algorithms currently incorporated in the system. Measurement of parameters for multi-speed bicycles, ensuring reliability of measured parameters under all conditions and quantification of metrological characteristics of the proposed system are to be carried out in the future work. Current state-of-the-art solutions for performance evaluation are limited to controlled environments and do not offer comprehensive assessment during rides. The proposed system has the potential to empower cyclists with on-the-field monitoring to comprehensively assess their rides and quantify their performance.

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