Mobile Sensing System for Cycling Power Output Control

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Abstract. This paper describes the development of a novel cycling effort control system that contributes to promote the users' physical health and mobility. This system controls the motor assistance level of an electric bicycle in order to ensure that the cyclist's power output remains inside the desired limits, regardless of changes in variables such as the speed of the bicycle or the slope of the terrain. The power output is monitored using a sensor device that provides raw torque and cadence data, whereas a smartphone application processes these data, implements the effort control algorithm and provides the user interface. Modules on the bicycle handle the data acquisition, wireless communication with the smartphone and driving of the motor assistance level. Experimental results validate the effectiveness of the implemented power output control system.

Keywords: effort control, power output, mobile sensing, electric bicycle.

1 Introduction

Mobile sensing is an emerging R&D area focused on the collection and processing of data from sensors located inside and/or around mobile devices [1,2,3]. One of the potential applications of these systems is the cycling effort control. Cyclists frequently exercise at different intensity levels depending on the intended goals. A common approach is to divide the exercise into different intensity zones, for example, below the lactate threshold (LT), between LT and the onset of blood lactate accumulation (OBLA4), and above OBLA4. These zones are usually calculated based on the measurement of the power output or heart rate [4,5].

Mobile sensing systems applied to cycling include the Copenhagen Wheel project [6], the Biketastic platform [7] and the BikeNet project [8]. These systems use different sensors (accelerometer, magnetometer, microphone, thermistor, CO_2, CO, NOx, torque, etc.), mobile operating systems (Android and iOS) and wireless networks for communication between the smartphone and the external sensors (IEEE 802.15.4, Bluetooth, etc.).

In [9], the authors present a cyclist's heart rate control system for a bicycle equipped with a Continuously Varying Transmission (CTV), composed by a heart rate monitor,

adfa, p. 1, 2011.

a smartphone and an Electronic Control Unit (ECU), which communicate with each other via Bluetooth. The smartphone is responsible for the heart rate control algorithm, whereas the ECU executes the low level CTV control. In [10], the authors describe a system designed to maintain a continuous level of exercise intensity around the aerobic threshold, through the control of the motor assistance of an electric bicycle. This system is based on the monitoring of pedaling rate and the oxygen uptake (using an oxygen mask). Unlike these systems, this work proposes a novel effort control system for control of the cyclist's power output, based on the measurement of the torque and cadence.

The system proposed in this paper allows the provision of automatic effort control, based on the use of an electric bicycle and a smartphone, in order to assure that the cyclist's power output remains inside the desired limits, regardless of changes in variables such as the slope of the terrain or the speed of the bicycle, contributing to promote the users' physical health and mobility.

This paper is organized as follows. Section 2 presents an overview of the components of the developed system and their interaction. Section 3 describes the smartphone application. Section 4 presents results from the experimental tests and the corresponding discussion. Finally, Section 5 presents the conclusions and future work.

2 System Overview

The main components of the proposed system are an Electric Bicycle (EB) and a smartphone. The EB used for the implementation and evaluation of this system is a prototype developed at the University of Minho (Fig. 1). In addition to the original EB components, this system introduces a torque and cadence sensor, a central processing module and a Bluetooth gateway. The rear wheel support was used during the laboratory tests.

Fig. 2 presents a detailed view of the interaction between the different blocks of the system. The microcontroller of the central processing module uses one ADC to read the torque signal and another one to read the battery level. A GPIO pin was configured to trigger an interrupt each time a pulse is generated by the cadence signal. These values are pre-processed in the microcontroller and aggregated into a data frame, which is sent to the Bluetooth gateway. This microcontroller uses its Serial Communication Interface (SCI) to communicate with the gateway, and its Serial Peripheral Interface (SPI) to communicate with the motor drive module. The Bluetooth gateway communicates with the smartphone using its radio interface.

The torque and cadence sensor was placed inside of the crankset, which ensures protection against external environment factors, and its standard dimensions allow compatibility with most types of bicycles. This device generates a linear analog torque signal in the range from –200 Nm to +200 Nm. It also generates pulses as the pedal is rotated, which enable the calculation of the cadence.

The smartphone application processes the received data and implements the power output control algorithm, which decides the required motor assistance level in real-time, based on the measured power output and the thresholds specified by the user.

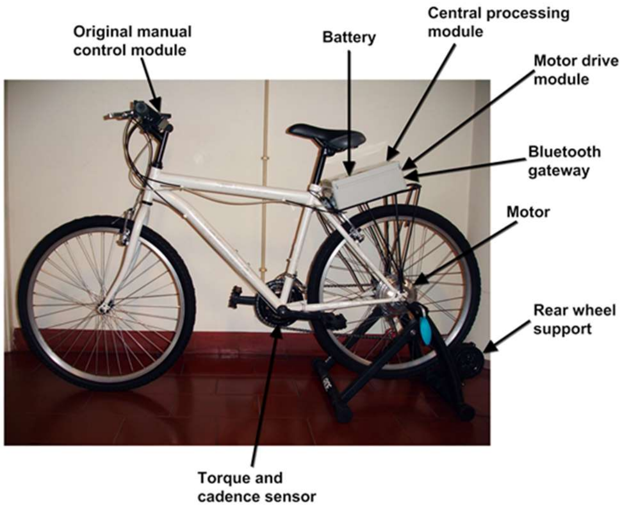

Fig. 1. Electric bicycle used in this work with the installed components.

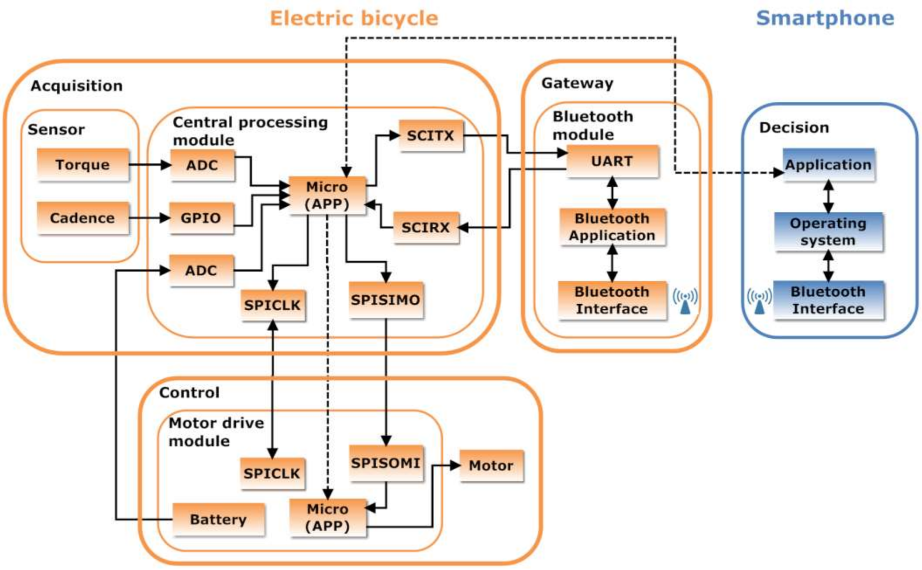

Fig. 2. Block diagram of the implemented system.

Fig. 3 represents the information flow between the components of the system. After the authentication with central processing module of the bicycle, the smartphone application gives the user the choice of the assistance mode: Manual mode, which allows the user to increase/decrease the motor assistance level though two buttons on the display; or Automatic mode, which allows the user then chooses the control mode: resistance mode, which considers only the measured torque; or power mode, which considers the power output calculated using both the cadence and the torque.

When the automatic mode is chosen, the application executes a loop code periodically. During this phase, the central processing module measures the time between pulses generated by the sensor, the torque and the EB battery level, and sends these data to the smartphone application, which calculates the cycling cadence, executes the effort control algorithm, and sends the decision back to the central processing module, which finally transmits it to the motor drive module to adjust the assistance level.

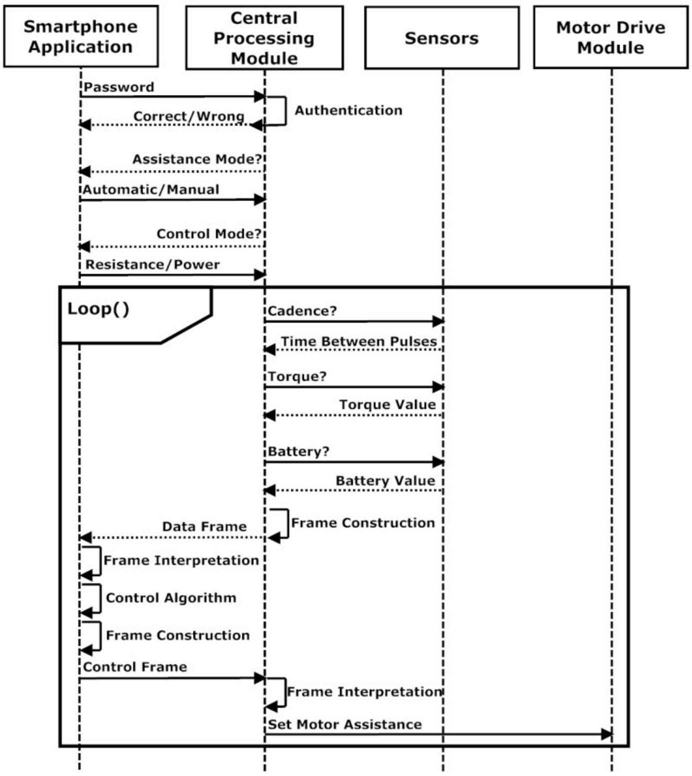

Fig. 3. Sequence diagram of information flow in the developed system.

3 Smartphone Application

The smartphone application was developed and tested using an HTC Sensation Android smartphone. This application processes the data generated by the torque and cadence sensor and executes the power output control algorithm.

Taking into account that the sensor generates 8 pulses per full rotation of the pedal, the cadence, in rpm, may be calculated by counting the number of pulses (N_p) during a given sampling period (T_s), through the use of the following equation:

$$C = \frac{60\ N_p}{8\ T_s} \tag{1}$$

This procedure works well when T_s is relatively large (more than 1 s). However, when this value is small (as in the case of this work, where a sampling period of 200 ms was used), the resulting resolution is too low, due to the small number of samples collected, as shown in Fig. 6.

In order to solve this problem, we replaced the procedure of counting the number of pulses over the sampling period by the measurement of the time elapsed between consecutive pulses (T_p). With this new procedure, the cadence is calculated using the following equation:

$$C = \frac{60}{8\ T_p} \tag{2}$$

The power output (P), in watts, can be obtained from the multiplication of the torque (τ), in Nm, and the angular velocity (ω) of the pedaling, in rad/s:

$$P = \tau\ \omega \tag{3}$$

where the angular velocity is obtained using the following equation:

$$\omega = \frac{2\pi C}{60} \tag{4}$$

Another problem encountered during the development of the effort control system is that the signal provided by the torque sensor presents very large variations as the cyclist presses and releases the pedal. Since the power output depends on the torque, its value presents large variations as well (see the lower part of Fig. 7). Therefore, it was necessary to smooth the abrupt changes in the power output, to provide a more stable input to the control algorithm, in order to avoid undesired changes on the motor assistance level. To that purpose, we used the Exponentially Weighted Moving Average (EWMA), which is based on the following equations, where $0 \leq \alpha \leq 1$. Smaller values of α increase the smoothing but make the output less responsive to changes in the input, and vice-versa.

$$S_k = X_k,\ k = 0 \tag{5}$$

$$S_k = \alpha X_k + (1-\alpha)\, S_{k-1}, k > 0 \tag{6}$$

Fig. 4 presents the implemented power output control algorithm. After receiving the sensor data, the smartphone application calculates the cadence and the power output, and then it applies the EWMA to smooth the power output. If the resulting value exceeds the maximum threshold defined by the user, the variable increaseAid is incremented, and, if both the motor assistance level (aidLevel) is lower than the maximum level and increaseAid is equal to 4, the variable increaseAid is cleared and the motor assistance level (aidLevel) is incremented; otherwise, the processing returns to the start of the algorithm. A similar procedure is performed when the EWMA value decreases below the minimum threshold.

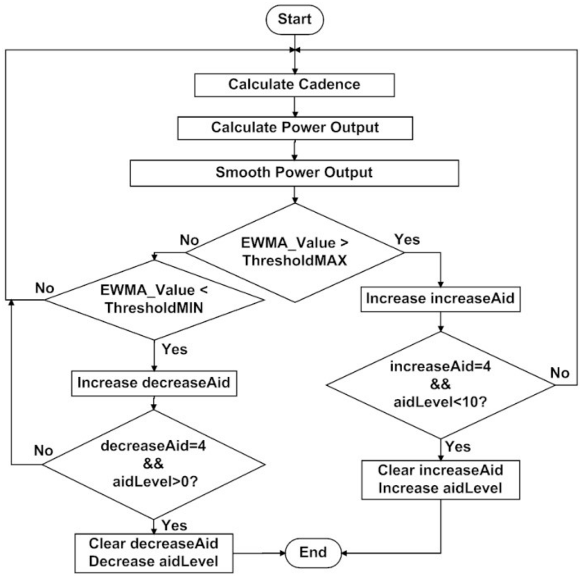

Fig. 4. Flowchart of the power output control algorithm.

The variables increaseAid and decreaseAid store pre-defined values that can be adjusted to guarantee that the motor assistance level is not prematurely changed in response to transitory changes in the effort.

4 Results and Discussion

The first tests performed aimed to characterize the end-to-end delay, from the moment the sensor data is collected until the motor assistance is applied. The rationale was to determine a suitable value for the sampling time in order to guarantee that a new sample is only acquired after the feedback from the previous sample was processed. The information flows from the bicycle to the smartphone and back, and the delay includes data processing times at the smartphone and the microcontrollers, as well as Bluetooth wireless transmission and medium access times. This test collected 3000 samples. Through the CCDF (Complementary Cumulative Distribution Function) of the end-to-end delay, presented in Fig. 5, it can be concluded that any value above 120 ms assures that the sampling time is higher than the delay. In the following tests, a sampling time of 200 ms was used.

The cadence value obtained through (1) provides low resolution, because, for normal values of cadence, the number of pulses generated during a short period of time is too low. Fig. 6 reflects this situation, where the measured cadence oscillates among a small number of levels. As referred in Section 3, this problem was solved by counting the time between consecutive pulses provided by the cadence sensor and using equation (2). The upper part of Fig. 7 shows that a much higher cadence resolution can be obtained through this method.

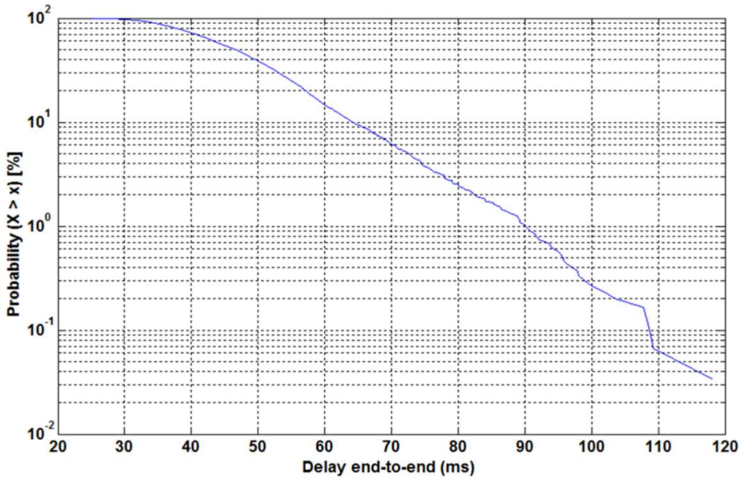

Fig. 5. Delay end-to-end complementary cumulative distribution function.

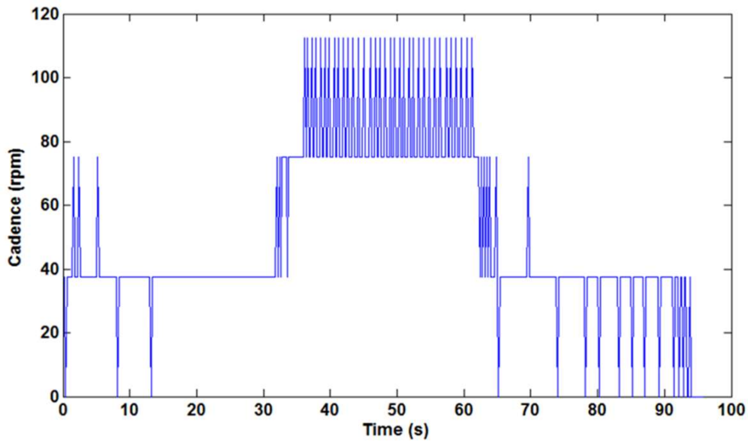

Fig. 6. Cadence measurement based on the number of pulses.

Two types of experimental tests were made to compare the measured power output without/with the control algorithm: 1) variable resistance with constant cadence; 2) variable cadence with constant resistance. These tests were performed with the rear wheel placed on a support that allows the adjustment of the resistance applied to the bicycle, and with the EWMA parameter set to $\alpha = 0.1$. Results from type 1 tests were similar to those presented previously in [11], whereas results from type 2 tests are presented in Fig. 7 (without control) and Fig. 8 (with control).

At the beginning of these tests, the cadence was kept around 30 rpm during the time interval from 5 s to 25 s, and was increased to 40 rpm between 25 s and 45 s. After 45 s, the cadence was decreased again to 30 rpm. Fig. 7 presents the behavior of the cadence and the power output for this scenario, without the use of the power output control algorithm. As the figure shows, the power output exceeds significantly, and during large periods, the maximum threshold defined.

In the case with the power output control algorithm enabled, shown in Fig. 8, the cadence pattern is similar to the previous one. As the figure shows, this effort control algorithm increases/decreases the motor assistance level when necessary, with the aim to maintain the average power output inside the defined thresholds. Due to limitations on the motor drive module of the electric bicycle, it was not possible to exceed the motor assistance level 4 (out of 10 defined levels), which imposed a constraint on the operation of the effort control algorithm, resulting in periods where the power output briefly exceeded the maximum threshold, because the algorithm was not able to increase the motor assistance as required anymore.

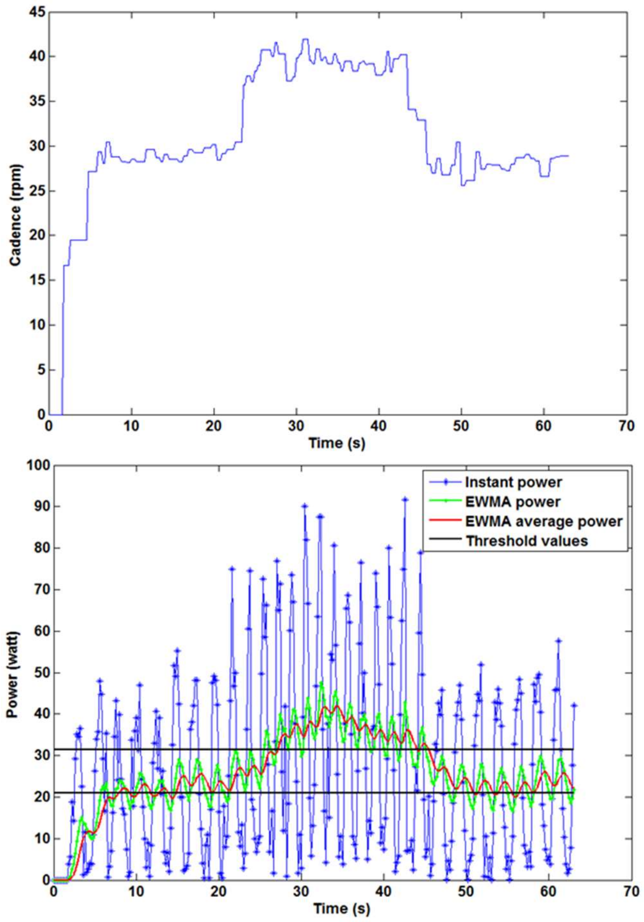

Fig. 7. Power output with variation of the cadence and without control.

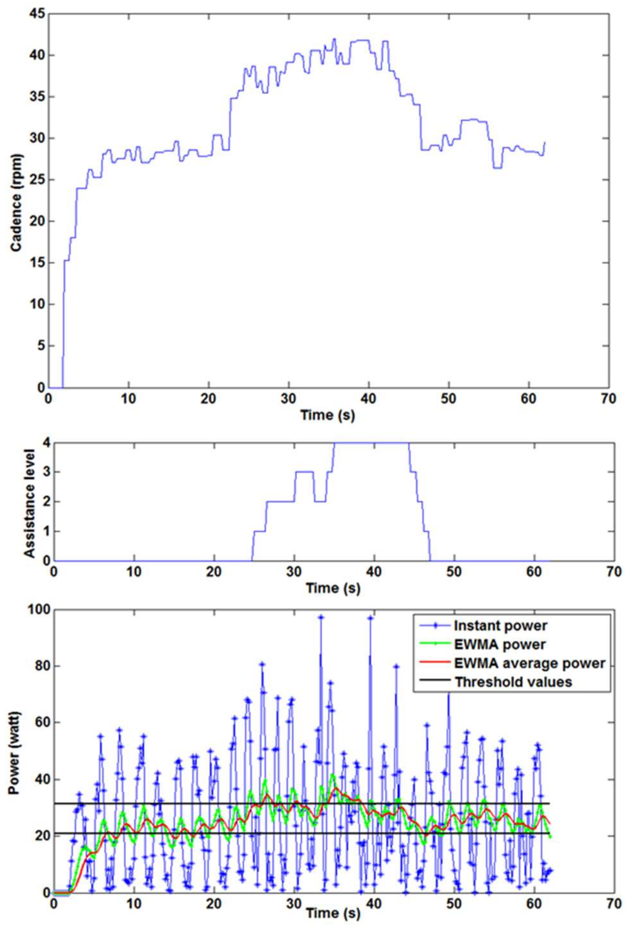

Fig. 8. Power output with variation of the cadence and with control.

5 Conclusions

This paper describes a system that enables cycling power output control through the use of a smartphone and an Electric Bicycle (EB). Experimental results validate the proposed system, which has applications on fitness, healthcare and transportation.

In the future it is intended to integrate functionalities of three other mobile sensing systems, which were developed in parallel, into this system. The first one provides a georeferenced database, which can be accessed online, with measurements of several relevant cycling parameters, and offers the functionalities of visualization of current and past routes in a map, sharing data with friends, joining or creating events, and locating friends [12]. The second one allows the monitoring of the posture of cyclists in real-time, using wireless motion capture sensors [13]. The third one provides personalized information to the cyclist, including EB range prediction and information regarding locally available public transport [14].

Future work includes also the integration in the same system of an effort control method based on the heart rate.

Acknowledgements

This work is supported by FCT (Fundação para a Ciência e Tecnologia) with the reference project UID/EEA/04436/2013, and by FEDER funds through the COMPETE 2020 – Programa Operacional Competitividade e Internacionalização (POCI) with the reference project POCI-01-0145-FEDER-006941.

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