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Optimal energy management in series hybrid electric bicycles☆

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ABSTRACT

Light electric vehicles are a viable way of reducing urban congestion and local pollutant emissions. Electric bicycles combine electrical and human power, hence they represent an appealing class of hybrid vehicles in such a context. Differently from other hybrid vehicles, the energy management of hybrid bicycles is little investigated in the literature. In this work, we study the problem for a series electric-human-powered hybrid architecture, in which there is no direct mechanical link between the pedals and the wheel. We tackle the problem using optimal control principles, aiming to minimize the perceived physical exertion while guaranteeing a predetermined electric range. We build on an approximated solution of the problem and propose a control system that copes with incomplete trip information. In a series of simulation and experimental tests, the proposed strategy approaches the acausal optimum and significantly improves performance if compared to a baseline causal policy; the discussion also encompasses the sensitivity of the results to the requested information.

1. Introduction

Electrical Power Assisted Bicycles (EPACs) are meeting growing success in every-day urban usage, due to their convenience in congested areas, to the absence of noise and pollutant emissions and to their efficient use of the energy stored in the battery (Alli, Formentin, & Savaresi, 2010). EPACs are a class of light Hybrid Electrical Vehicles (HEVs), in that they combine the electrical energy stored in the battery with human power. While hybridization is extensively studied for passenger vehicles and trucks (Ambühl & Guzzella, 2009; Guzzella & Sciarretta, 2007; Larsson, 2014; Manzie, Dewangan, Corde, Grondin, & Sciarretta, 2015; Musardo, Rizzoni, Guezennec, & Staccia, 2005; Sampathnarayanan, Onori, & Yurkovich, 2014; Sciarretta & Guzzella, 2007; Sciarretta, Guzzella, & Back, 2004; Sciarretta et al., 2014; Serrao, Onori, & Rizzoni, 2009; van Keulen, Gillot, de Jager, & Steinbuch, 2013), energy management of Hybrid Electrical Bicycles (HEBs) has not received as much attention in the literature.

The existing literature is mainly devoted to parallel HEBs, in which the mechanical power at the wheel is supplied by the cyclist and a motor. As in passive bicycles, the cyclist's cadence and the vehicle velocity are kinematically linked. Most products on the market let the cyclist determine the level of assistance, without explicitly accounting for energy efficiency or human dynamics. In Fayazi, Lucich, Vahidi, and Mocko (2013) and Wan, Fayazi, Saeidi, and Vahidi (2014) the optimal pacing to complete a track in minimum time is computed using a model of muscular fatigue; however, the approach is not for online implementation. An online energy management approach for a Full HEB is presented in Spagnol et al. (2012), Spagnol, Corno, Mura, and Savaresi (2013) and Spagnol, Corno, and Savaresi (2013): the algorithm improves the rider's metabolic efficiency, reduces perceived muscular fatigue and sustains the charge of the battery, which needs not be recharged from the grid. The effects on the cyclist's fatigue have been experimentally investigated as well.

Series HEBs lack the mechanical connection between the pedal and the wheel, as the power transmission is purely electric. This in principle lets the cyclist always pedal in optimal conditions, and provides more freedom to the designer to influence the pedal feel and the cyclist's effort (Fuchs, 2015; Mando Footloose, 2017). Possible practical applications include a light Electrical Vehicle (EV) with a human, emission-free range extender, and a moving exercise bike. On another front, the *chainless* concept opens several control problems, such as ensuring a comfortable feeling at the

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(a) Visual interface for the cyclist.

(b) *HR* monitor.

(c) Instrumented prototype of the chainless bicycle SeNZA.

Fig. 1. Some details of the setup employed in the experiments.

pedals or managing the dispatch of traction power between the battery and the cyclist.

In this paper, we address the real-time optimal energy management of series HEBs and test it experimentally. Our benchmark is SeNZA, the prototype depicted in Fig. 1 and previously presented in Corno, Berretta, and Savaresi (2015); Corno, Roselli, and Savaresi (2016). The goal is here to minimize an index of perceived exertion and to cope with a constraint on the final state of charge of the battery, to avoid excessive depletion before a charging station is available.

With this goal in mind, a review of the physiologic literature suggests to use a cost function based on the cyclist's heart rate; this variable is also easily measurable, therefore model identification and real-time implementation are simplified. In Guanetti, Formentin, Corno, and Savaresi (2015), the same setup was the base for an acausal solution study, comparing two approaches based on Pontryagin's Minimum Principle. The first approach was the so-called indirect technique to numerically solve Optimal Control Problems (OCPs) (Rao, 2009). The second approach was tailored for the series HEB, showing that an approximated technique attains close-to-optimum performance concentrating the knowledge of future cycling conditions in a single tuning parameter. A similar result is known in the literature on the Equivalent Consumption Minimization Strategy (ECMS) (Sciarretta & Guzzella, 2007) for the energy management of HEVs.

In this paper, we build on this approximated approach and propose a real-time strategy, in which the tuning parameter is adapted online to the current cycling conditions. The strategy can use a forecast of the elevation profile, to improve performance and enhance the use of battery charge, especially on hilly routes. While the focus is here on series HEBs, the approach could also be applied to parallel HEBs. An intuitive, simple strategy is also proposed as a baseline. In the proposed simulations, the approach performs closely to the acausal optimum, and outperforms the baseline. A sensitivity study investigates the dependence of these results on the elevation profile. Experimental results are in line with those from simulations, and suggest that the approach can have practical interest.

The paper is structured as follows. The architecture of the chainless bicycle is introduced in Section 2, while the model of the human-electric powertrain is detailed in Section 3. After presenting a baseline strategy in Section 4, the proposed energy management strategy is discussed in Section 5. Section 6 presents the corresponding simulation results, while Section 7 summarizes the experimental results.

2. System architecture

The test vehicle, depicted in Fig. 1, is the prototype of SeNZA, a series HEB developed by the mOve research group at the Politecnico di Milano and zeHus srl. For a detailed description of the prototype the reader is referred to Corno et al. (2015, 2016). In sum, the bicycle is equipped with:

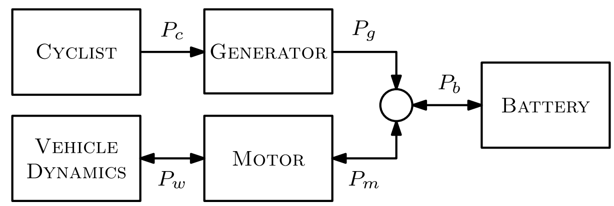

Fig. 2. Conceptual scheme of the series HEB.

- A 500 W brushless DC traction motor/generator connected to the rear wheel.
- A 250 W brushless DC generator linked to the pedals.
- Two custom made Electronic Control Units (ECUs) to control the generator and motor. The generator ECU hosts the energy management system described in this paper. Measurements of motors and battery currents, vehicle velocity and pedal cadence are also available.
- A battery pack, with a Battery Management System (BMS) that performs several safety checks and estimates the state of charge *SoC* based on current and voltage measurements using a Kalman filter (Spagnol, Rossi, & Savaresi, 2011).
- Two brake switches, to detect friction braking.
- A CAN bus for the communication between all the ECUs and a data logger.
- A Mio ALPHA Heart Rate Monitor (see Fig. 1) to measure the cyclist's heart rate *HR*.

Fig. 2 depicts the functional representation of the powertrain. Differently from standard HEVs, the prime mover is a cyclist and not a thermal machine. The *energy management system* splits the motor power P_m between battery power P_b and generated power P_g. The motor power P_m depends on the wheel power P_w, while the generated power P_g is a function of the output power of the cyclist P_c. As the arrows in Fig. 2 show, power can only flow from the cyclist to the generator, to either recharge the battery or supply the motor. The motor works as a generator when the wheel power is negative and regenerative braking is performed (Corno et al., 2015, 2016).

The control algorithm outputs the optimal amount of electrical power P_g that the cyclist should generate. Differently from other HEVs, P_g cannot be directly enforced, since it ultimately depends on the cyclist's power output. Hence, a lower layer is introduced to control the human generator in our experiments. The optimal value of P_g is sent via CAN bus to a visual interface (see again Fig. 1) that shows to the cyclist the difference between suggested and