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Model-based control for an innovative power-assisted bicycle

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Abstract

This paper presents an activity concerning the development of a control strategy for power-assisted electric bicycles, also called pedelecs. A common assistance algorithm available on commercial pedelecs consists in providing predefined constant assistance electric power. This approach is lack of flexibility with respect to environmental condition and generally does not provide a good driving comfort. The proposed control method has been designed to minimize the tracking error between the actual bike velocity and the desired one, in the presence of external disturbances. The assistance electric motor torque consists of a feedforward torque integrated with a feedback one. The feedforward contribution is a nonlinear torque based on the pedelec model. The feedback action has the function to compensate the tracking error due to model uncertainties and unknown disturbances. The performance of the methodology has been evaluated applying the controller to an innovative pedelec prototype. To this aim, a mathematical model of the vehicle has been developed. Different human torque models have been implemented in order to study the influence of the rider on the pedelec dynamics. The results of a comparative analysis between the proposed algorithm and a common assistance method have demonstrated that the proposed controller provides improvements in terms of riding comfort and energy utilization.

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Keywords: pedelec, power-assisted bicycle, control, quality of riding, energy consumption

1. Introduction

Continuous improvements in technology and ways to make vehicles more environmental friendly has led to an increase of so-called green vehicles [1]. Among the latters, light electric vehicles, such as electric bicycles, are very effective for city commuters [2, 3].

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Electric bicycles, also called e-bikes, can be a viable solution to the world's energy crisis because they can substitute motor vehicles for midrange transportation needs with zero emission. Indeed, a vehicle as the e-bike [4, 5] constitutes an alternative vehicle for both personal mobility and goods delivery, especially for small and medium distances. The e-bike, in all its forms, two or three wheels (tricycle), is able to move with an average speed equal to the typical one of the town traffic and, at the same time, it requires energy for its mobility that is very close to the necessary energy just for the displacement of the transported people.

There are two kinds of electric bicycle. A first kind includes an electric motor into bicycle frame or wheels, and it is driven by motor using a handlebar throttle [6, 7]. A second kind is a power-assisted bicycle, also called pedelec [9], which is a human–electric hybrid bicycle [10] that supports the rider with electric power only when the rider is pedaling. Typical e-bikes are equipped with an electric motor, a battery, a control unit and sensors to detect rider torque and bicycle speed. The motor torque, determined by the control unit, plays a crucial role in ensuring the comfort and the safety of pedelec riding.

This paper is dedicated to developing a pedelec velocity control (PVEC) with both the electric torque from the motor and assistant torque from the rider. The ultimate objective of the PVEC is to follow a given velocity command under the limited motor electric torque, the rider torque and the inevitable disturbance actions caused by environmental conditions such as the wind and the road surface.

In [11 – 13], an e-bike velocity control, based on a fuzzy logic control approach, has been investigated. The studies in [14, 15] inspected the effect of the human assistant torque from the rider. In [16, 17], an e-bike velocity control has been proposed in terms of optimization of H^{∞} performance.

For this study of velocity control for pedelec, the torque control law has been obtained with a feedforward control integrated with a feedback one. The feedforward control law is a nonlinear torque obtained from the vehicle mathematical model. The feedback action is based on a proportional-integral-derivative (PID) control that has the function to compensate the tracking error due to model uncertainties and unknown disturbances. The PVEC has been applied to a pedelec prototype and the results have been compared with the ones resulting from a classical assistance method. The performance of the PVEC, in terms of velocity tracking, stability and disturbance rejection, have been optimized by properly setting the PVEC coefficients. The quality of riding for the two different assistance methods has also been evaluated.

The rest of the paper is organized as follows: in section 2 the vehicle description is presented; the derivation of the pedelec mathematical model is showed in section 3; the PVEC development is described in section 4; finally, simulation results are illustrated in section 5.

2. Vehicle description

A prototype of an innovative power-assisted bicycle has been adopted for the research. The vehicle has been designed at the Department of Industrial Engineering of the University of Naples Federico II [18]; its scheme is shown in Fig. 1, where two components are highlighted: the electric motor and the chain force sensor.

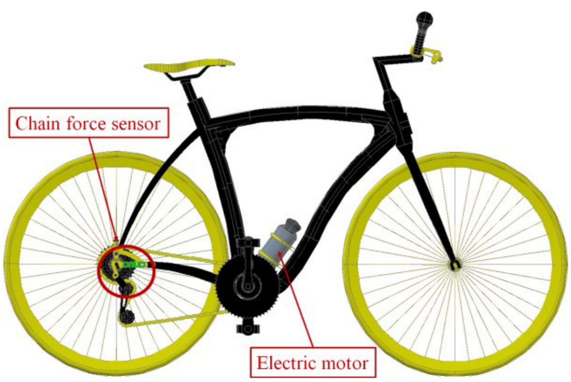

Fig. 1. Pedelec prototype scheme.

Generally, in commercially-available pedelecs the electric motor is located on one of the three hubs of the bicycle. A basic idea of the pedelec prototype consists of a central motor located in a battle, as shown in Fig. 1.

The pedelec prototype equips a new low cost system for the measurement of the chain force. The device is based on the employment of a load cell and suitable constraints that link the sensor to the bicycle frame, in order to make the measured force as close as possible to the chain one [19].

The motion transmission from the motor to the pedal shaft is achieved by two different gearboxes: the first one is a planetary gearbox and the second one is a simple bevel gear. The total transmission ratio is 1:25. Fig. 2 shows a scheme of the second gearbox location.

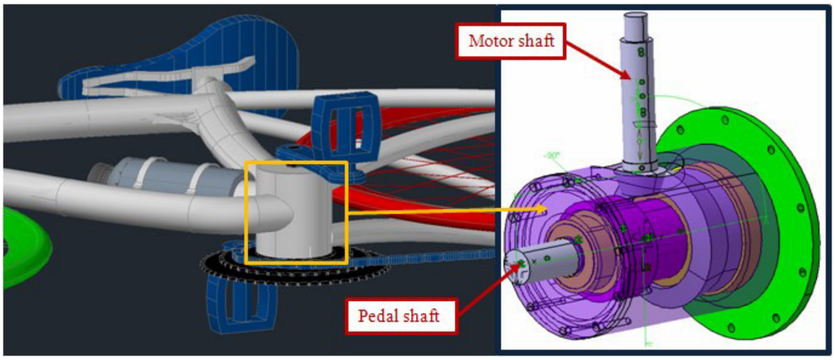

Fig. 2. Mechanical transmission between the motor shaft and the pedal one.

3. Pedelec mathematical model

With reference to Fig. 3, the bicycle longitudinal dynamics can be expressed as

$$M\frac{dv}{dt} = -F_w - F_{rr} - F_\alpha + F_t \quad (1)$$

where M is the total mass of the pedelec (including the rider), v is the pedelec longitudinal velocity and t is the time. The term F_w in (1) is the aerodynamic drag force:

$$F_w = \frac{1}{2} A_s C_w \rho_{air} v^2 \quad (2)$$

where A_s is the reference area of the bicycle-rider system, C_w is the aerodynamic drag coefficient, ρ_{air} is the air density.
The term F_{rr} (with reference to Fig. 3, F_{rr} is the sum of its two components $F_{rr,r}$ and $F_{rr,f}$, acting on the rear and front wheels) is the rolling resistance force:

$$F_{rr} = C_{rr} M g \cos(\alpha) \quad (3)$$

where g is the gravitational acceleration, α is the slope of the road, C_{rr} is the rolling resistance coefficient.
The gradient resistance force F_α is formulated as

$$F_\alpha = Mg\sin(\alpha)\,. \quad (4)$$

Finally, F_t is the total thrust force provided by the motor and the rider.

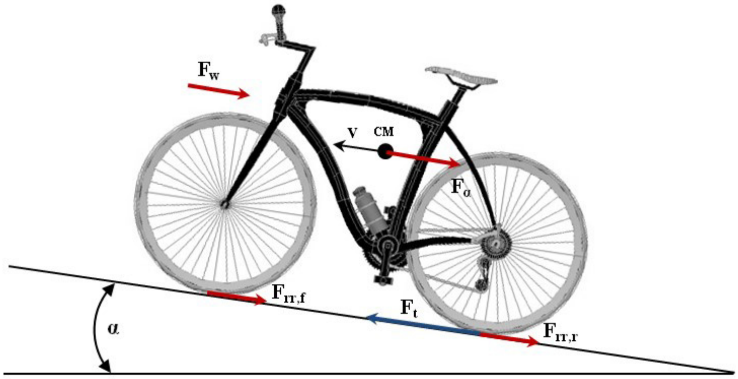

Fig. 3. Longitudinal components of forces acting on the pedelec.

The bicycle longitudinal dynamics can be expressed in function of the total driving torque $T_{d,w}$ applied to the rear wheel

$$T_{d,w} = r\left(M\frac{dv}{dt} + F_w + F_{rr} + F_\alpha \right), \tag{5}$$

where r is the nominal radius of both the bicycle wheels.
Introducing the gear ratio ε_g and the efficiency η_g of the bicycle gearbox

$$\begin{aligned} \varepsilon_g &= \frac{\omega_p}{\omega_w} \\ \eta_g &= \frac{T_{d,w}\omega_w}{T_{d,p}\omega_p} = \frac{T_{d,w}}{T_{d,p}\varepsilon_g} \end{aligned}, \tag{6}$$

it is possible to obtain the expression of the driving torque $T_{d,w}$ relative to the pedal shaft:

$$T_{d,p} = \frac{r}{\eta_g \varepsilon_g}\left(M\frac{dv}{dt} + F_w + F_{rr} + F_\alpha \right) = T_h + T_{m,p}, \tag{7}$$

where ω_w is the angular velocity of the bicycle wheels, ω_p is the pedal angular velocity, T_h and $T_{m,p}$ are the human and the motor torque applied to the pedal shaft, respectively.
Considering the aforementioned gearboxes between the motor and the pedal shaft, characterized by a gear ratio ε_m and an efficiency η_m defined as

$$\begin{aligned} \varepsilon_m &= \frac{\omega_m}{\omega_p} \\ \eta_m &= \frac{T_{m,p}\omega_p}{T_m\omega_m} = \frac{T_{m,p}}{T_m\varepsilon_m} \end{aligned} \tag{8}$$

the torque equilibrium at the motor shaft can be derived:

$$T_m = \frac{r}{\eta_g \eta_m \varepsilon_g \varepsilon_m}\left(M\frac{dv}{dt} + F_w + F_{rr} + F_\alpha\right) - \frac{T_h}{\eta_m \varepsilon_m}, \tag{9}$$

where ω_m is the motor angular velocity and T_m is the torque provided by the electric motor applied to its shaft. Equation (9) can be rewritten considering equations (2)-(4) and expressing all the angular velocities with respect to the motor one:

$$\frac{Mr^2}{\eta_g \eta_m \varepsilon_g^2 \varepsilon_m^2}\frac{d\omega_m}{dt} + \frac{A_s C_w \rho_{air} r^3}{2\eta_g \eta_m \varepsilon_g^3 \varepsilon_m^3}\omega_m^2 + \frac{C_{rr} Mgr}{\eta_g \eta_m \varepsilon_g \varepsilon_m}\cos(\alpha) + \frac{Mgr}{\eta_g \eta_m \varepsilon_g \varepsilon_m}\sin(\alpha) = T_m + \frac{T_h}{\eta_m \varepsilon_m}. \tag{10}$$

The differential equation (10) can be rearranged as

$$J_{eq}\frac{d\omega_m}{dt} + B_{nl}\omega_m^2 = T_m + \frac{T_h}{\eta_m \varepsilon_m} + d. \tag{11}$$

where the following statements have been adopted:

$$\begin{aligned} J_{eq} &= \frac{Mr^2}{\eta_g \eta_m \varepsilon_m^2 \varepsilon_g^2}, \\ d &= -\frac{Mgr}{\eta_g \eta_m \varepsilon_g \varepsilon_m}\left[C_{rr}\cos(\alpha) + \sin(\alpha)\right], \\ B_{nl} &= \frac{A_s C_w \rho_{air} r^3}{2\eta_g \eta_m \varepsilon_m^3 \varepsilon_g^3}, \end{aligned} \tag{12}$$

Equation (11) describes a nonlinear first order system with three inputs: T_h from the human; T_m from the motor; and d from the environment.

4. Pedelec velocity control algorithm

The control scheme is presented in Fig. 4. The PVEC is designed to follow a desired velocity v_d imposed by the rider. The target velocity is relative to a desired assistance level, for example, a target pedelec velocity equal to 25 km/h corresponds to the maximum motor assistance level (100 %), instead, a desired velocity of 15 km/h involves a 60 % assistance level.

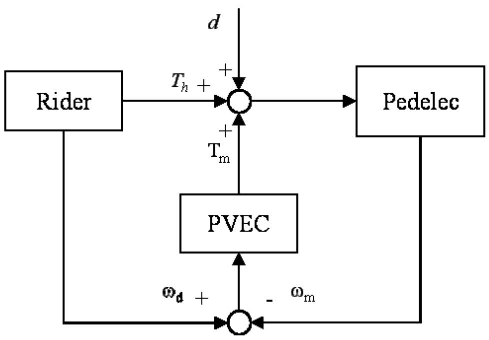

Fig. 4. Pedelec control scheme.

The control action consists in the motor torque T_m, while the control feedback is the pedal angular velocity ω_p obtainable with a proximity sensor. The rider pedaling torque, estimated via the chain force measurement, is used only for the activation of the PVEC. In particular, whenever the rider torque exceeds a limit value, the additional motor torque will be provided by the controlled electric motor. With reference to Fig. 4, the target motor angular velocity ω_d and the actual motor one ω_m have been calculated starting from the desired velocity and the pedal angular velocity:

$$\omega_d = \frac{v_d}{\varepsilon_g \varepsilon_m r} \qquad \omega_m = \frac{\omega_p}{\varepsilon_m} \tag{13}$$

The control requirements can be synthesized in three main performance objectives: desired velocity tracking, stability and disturbance robustness. These specifications have been taken into account with a mixed control approach constituted by a feedforward control torque $T_{m,ff}$ and a PID-based feedback one $T_{m,PID}$ (Fig. 5).

The feedforward action has been derived from the pedelec mathematical model (11) in order to compensate the inertial torque and the nonlinear aerodynamic resistance torque relative to the desired motor angular velocity ω_d:

$$T_{m,ff} = J_{eq}\frac{d\omega_d}{dt} + B_{nl}\omega_d^2 \tag{14}$$

The PID-based feedback assistance torque is the sum of proportional, integral, and derivative actions, weighted according to independent gain parameters K_P, K_I, and K_D. A filter in series with the derivative action has been implemented, where the coefficient K_N sets the location of the pole in the derivative filter.

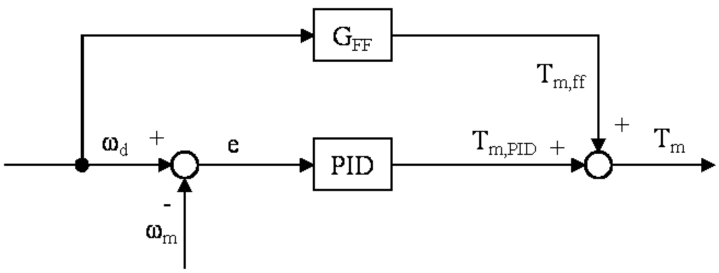

Fig. 5. PVEC control algorithm.

The PVEC feedback control action expressed in Laplace domain is:

$$T_{m,PID} = \left[K_p + K_I\left(\frac{1}{s}\right) + K_D\left(\frac{K_N s}{s+K_N}\right)\right]e \tag{15}$$

where e is the control error ($e = \omega_d - \omega_m$).

The tuning of the PVEC feedback torque has been performed in order to achieve a balance between tracking performance, stability and robustness.

Fig. 6a shows the unitary step reference tracking response of the closed-loop system, while its disturbance rejection performance is presented in Fig. 6b. The disturbance location has been implemented at plant input.

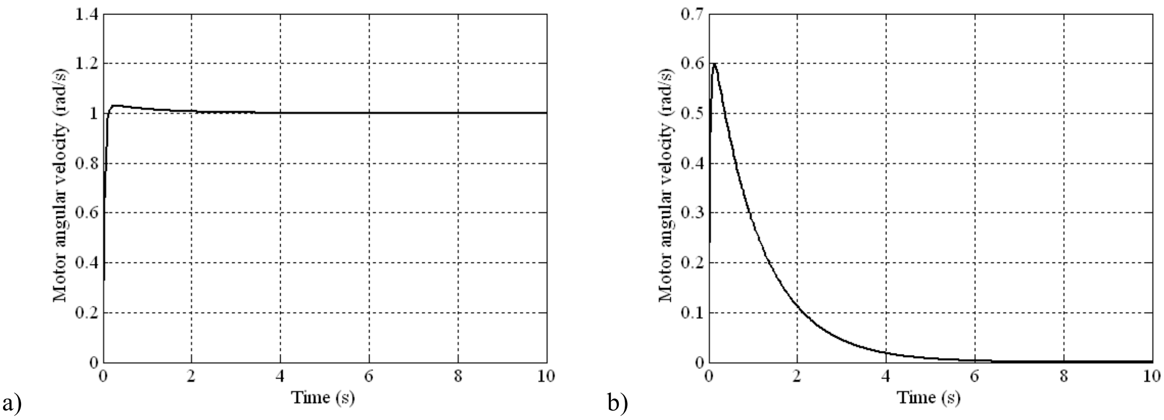

Fig. 6. PVEC feedback control performance. a) Step response; b) Disturbance rejection.

Results of Fig. 6a highlight a good tracking performance of the closed-loop system, moreover, the disturbance rejection can be also considered acceptable as shown in Fig. 6b.

The PVEC feedback control parameters and performance are collected in Table 1.

Table 1. Parameters and performance of the PVEC feedback control.

Description	Value
Proportional gain K_P	1.53
Integral gain K_I	1.35
Derivative gain K_D	-0.007
Filter coefficient K_N	212
Rise time (s)	0.07
Settling time (s)	0.77
Overshoot (%)	3.07
Gain margin (db @ rad/s)	-Inf @ 0
Phase margin (deg @ rad/s)	81.4 @ 24.3
Closed-loop stability	Stable

5. Simulation results

The PVEC has been tested on the full nonlinear model (11). The slope profile for testing the PVEC for urban riding within 7 km is shown in Fig. 7.

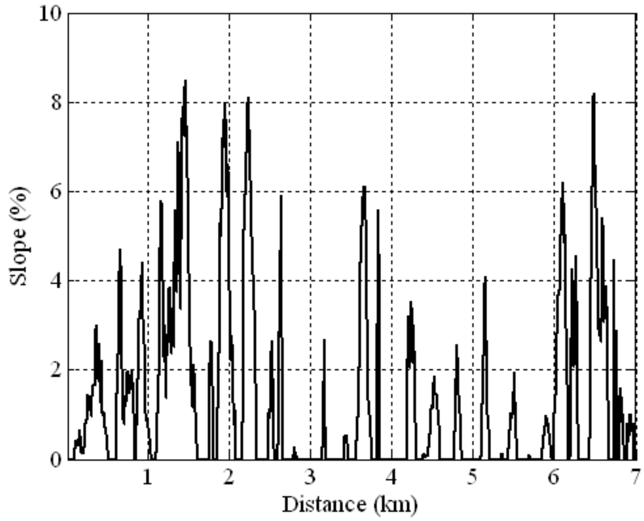

Fig. 7. Slope profile.

The pedelec specifications and environmental parameters are listed in Table 2.

Table 2. Model parameters.

Model parameter	Value
M (kg)	90
r (m)	0.3
η_m (-)	0.95
η_g (-)	0.98
ε_m (-)	25
ε_g (-)	0.47
C_w (-)	0.9
C_{rr} (-)	0.003
A_s (m^2)	0.4
ρ_{air} (kg/m^3)	1.225
g (m/s^2)	9.81

Two different rider models, characterized by different performances in terms of torque capacity, have been considered; the first one (RIDA) provides a constant torque of 10 Nm and the second one (RIDB) can provide a constant torque of 15 Nm. Both the riders reduce the applied torque to 2 Nm when the pedelec velocity exceeds the desired velocity, fixed to 15 km/h.

Figs. 8a and 8b show the comparison between the target and the effective pedelec velocity for both the riders.

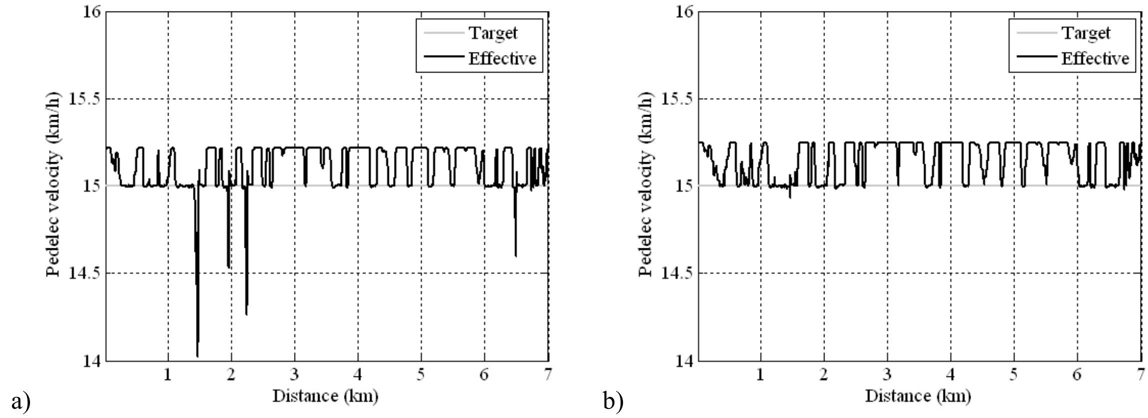

Fig. 8. Target and effective pedelec velocity. a) RIDA; b) RIDB.

The results of Fig. 8a show that for RIDA the reduced power effort of the rider involves track intervals where the pedelec velocity is less than the target one. In particular, in these intervals the motor power reaches its saturation limit, so, the motor cannot give the power necessary for maintaining the effective pedelec velocity at the desired level. This phenomenon is more clear considering the motor power diagrams showed in Fig. 9a and Fig. 9b.

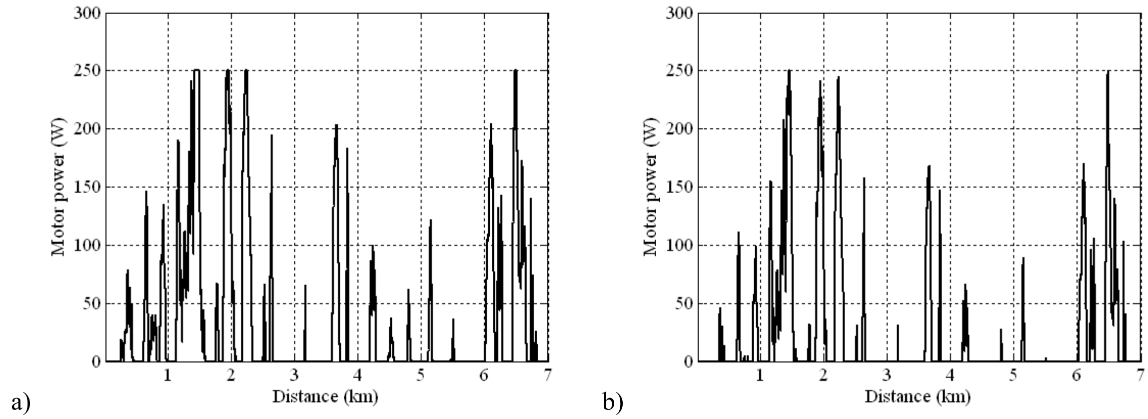

Fig. 9. Motor power. a) RIDA; b) RIDB.

In the case of RIDB the effective pedelec velocity is practically equal to the desired one (see Fig. 8b), in that case the motor power is always less than or equal to its saturation limit (see Fig. 9b). It is important to note that for both the cases the pedelec velocity exceeds 15 km/h, indeed when the actual velocity is higher than the target one the motor cannot provide resistance torque, therefore, the pedelec velocity is totally controlled by the rider. However, the simulation results, for both rider models, clearly show good performance of the proposed PVEC.

For comparison purposes, the proposed assistance method has been compared with a conventional assisted power method, which is the constant-assisted power (CAP). In the CAP method the rider is assisted by the motor with a predetermined constant power [20]. The CAP method is simple to implement, however, the same predefined assisted power is provided without considering the riding environment such that the comfort and the safety of the rider might not be guaranteed.

Simulations have been performed adopting the following statement:

- assisted power of the CAP: 25% of the maximum power (62.5 W);
- rider model: RIDB;
- target velocity: 16 km/h.
- slope profile: diagram of Fig. 7.

The two methods have been evaluated in terms of quality of riding results. For a pedelec riding condition, quality of riding refers to energy utilization, comfort and safety [21]. The comfort in pedelec riding consists in maintaining the vehicle under a preferred velocity when the assisted power is provided in collaborating with the rider power. Stability in controlling the pedelec is strictly related to instantaneous acceleration generated by the assisted power control. With abrupt assisted power, the instantaneous acceleration will be too large or too small to cause instability in controlling the pedelec such that the rider will feel unsafe in riding. So, the comparison results are collect in terms of pedelec velocity, instantaneous pedelec acceleration and energy consumption.

Figs. 10a and 10b show the velocity records for CAP and PVEC, respectively.

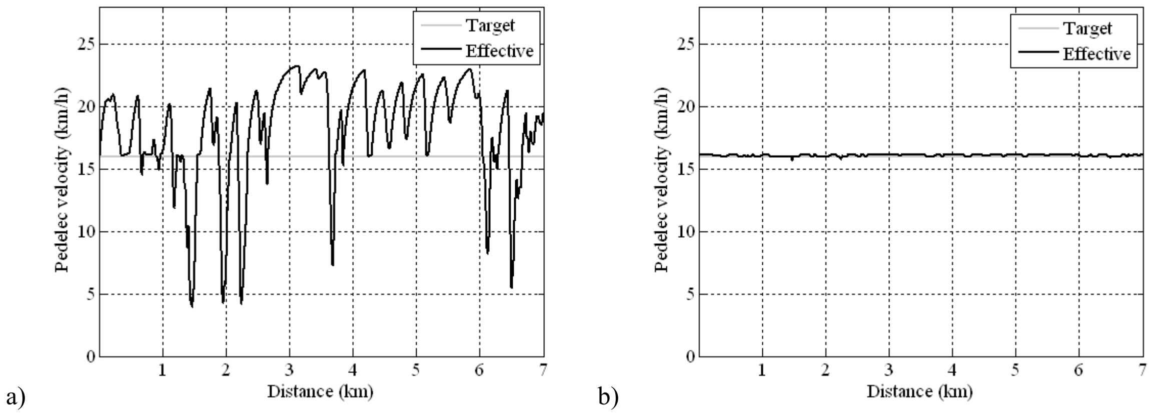

Fig. 10. Target and effective pedelec velocity. a) CAP; b) PVEC.

Concerning Fig. 10a, the velocity trace of the CAP is fluctuating, even if the medium value of the velocity is about 16 km/h the comfort index is poor. On the contrary, the pedelec velocity trace adopting PVEC shows that the target vehicle velocity is almost maintained all the way, starting from the beginning until the end of the ride. It evidences that the PVEC is able to exercise the appropriate assisted power for supporting the rider in order to satisfy the comfort criteria.

Diagrams of the instantaneous accelerations of the pedelec for CAP and PVEC are shown in Fig. 11a and Fig. 11b, respectively.

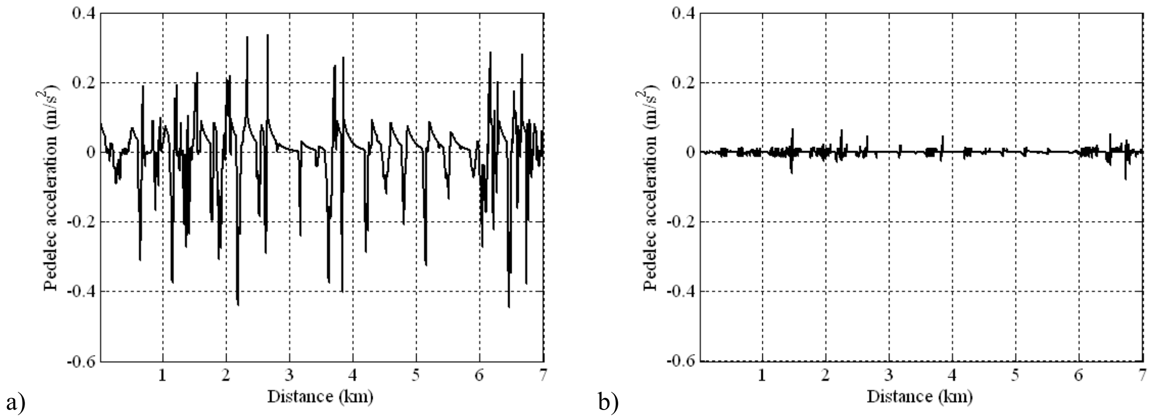

Fig. 11. Pedelec instantaneous acceleration. a) CAP; b) PVEC.

The trace of the instantaneous accelerations of the pedelec for PVEC, showed in Fig. 11b, demonstrates that the instantaneous acceleration is less than that one obtained with CAP method (see Fig 11a), which means that the safety and the stability of the pedelec, maintained by the PVEC, is better as compared with CAP method.

The motor energy consumption for CAP and PVEC, are shown in Fig. 12a and Fig. 12b, respectively, to highlight how the energy is utilized.

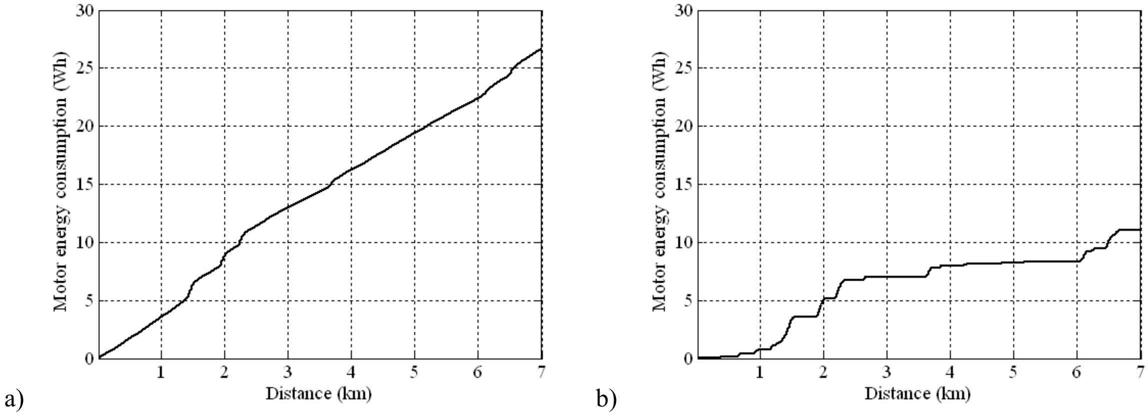

Fig. 12. Motor energy consumption. a) CAP; b) PVEC.

Among the compared methods, the PVEC consumes the least energy, which is 11.1 Wh, as compared with the motor energy consumed by the CAP method equal to 26.6 Wh. Also in this case the proposed PVEC demonstrates its better performance compared with the CAP method.

6. Conclusion

In this paper, a velocity control for a pedelec has been proposed. Firstly, a mathematical model has been derived considering the structure of an innovative pedelec. Subsequently, a mixed controller, composed by a feedforward action and a feedback one, has been designed in order to provide an assistance motor torque suitable to follow a target bicycle velocity, imposed by the rider. The controller has been validated on the pedelec mathematical model. Simulation results have confirmed that the proposed assistance torque algorithm achieves better energy utilization and quality of riding by comparing with a conventional assisted power method.

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References

[1] Emadi A, Lee YJ, Rajashekara K. Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles. IEEE Trans. Ind. Electron 2008; 55:6, pp. 2237–2245.

[2] Iodice P, Abagnale C, Cardone M, Strano S, Terzo M, Vorraro G. Performance evaluation and environmental analysis of an electrically assisted bicycle under real driving conditions. In proceedings of the ASME 2014 12th Biennial Conference On Engineering Systems Design and Analysis – ESDA2014, Copenhagen, Denmark, 2014.

[3] Iodice P, Senatore A. Experimental-analytical investigation to estimate an emission inventory from road transport sector. IAENG Transactions on Engineering Sciences - Special Issue of the International MultiConference of Engineers and Computer Scientists, IMECS 2013 and World Congress on Engineering, WCE 2013, 2014, pp. 141-149.

[4] Tsai CC, Huang HC, Lin SC. Adaptive neural network control of a self-balancing two-wheeled scooter,” IEEE Trans. Ind. Electron. 2010; 57:4, pp. 1420–1428.

[5] Muetze A and Tan YC. Electric bicycles: A performance evaluation. IEEE Ind. Appl. Mag. 2007; 13:4, pp. 12–21.

[6] Fairley P. China's cyclists take charge: Electric bicycles are selling by the millions despite efforts to ban them. IEEE Spectr. 2005; 42:6, pp. 54–59.
[7] Somchaiwong N and Ponglangka W. Regenerative power control for electric bicycle. In Proc. IEEE Int. Joint Conf. SICE-ICASE 2006; pp. 4362–4365.
[8] Yang MJ, Jhou HL, Ma BY, Shyu KK. A cost-effective method of electric brake with energy regeneration for electric vehicles. IEEE Trans. Ind. Electron. 2009; 56:6, pp. 2203–2212.
[9] Schneider D. Easy rider: Convert your bicycle to a human–electric hybrid. IEEE Spectr. 2009; 46:9, pp. 26–27.
[10] Du W, Zhang D, Zhao X. Research on battery to ride comfort of electric bicycle based on multi-body dynamics theory. In Proc. IEEE Int. Conf. Autom. Logistics, Aug. 2009; pp. 1722–1726.
[11] Chen PH. Intelligent application: ELEBIKE fuzzy control: Part 1. In Proceedings of the Seventh International Conference Machine Learning and Cybernetics, Kunming, China, IEEE Computer Society, Piscataway, NJ, 2008, pp. 3581–3585.
[12] Indulal S and Nair PSC. A novel approach in automatic control of a hybrid bicycle. In Proceedings of the IETUK International Conference on Information and Communication Technology in Electrical Sciences, Chennai, India, Institution of Engineering and Technology, Stevenage, 2007, pp. 296–301.
[13] Liang CY, Lin WH, Chang B. Applying fuzzy control to an electric bicycle. In Proceedings of First International Conference on Innovative Computing, Information and Control, Beijing, China, IEEE Computer Society, Piscataway, NJ, 2006, pp. 513–516.
[14] Niki H, Miyata J, Murakami T. Power assist control of electric bicycle taking environment and rider's condition into account, in Proceedings of the International Society for Optical Engineering, Sappora, Japan, paper no. 60520H, The International Society for Optical Engineering, Bellingham,WA, 2005.
[15] Fan X, Iwase M, Tomizuka M. Non-uniform velocity profile compensation for an electric bicycle based on repetitive control with sinusoidal and non-sinusoidal internal models. In Proceedings of the ASME Dynamic Systems and Control Conference, Hollywood, CA, American Society of Mechanical Engineers, NewYork, 2010, pp. 765–772.
[16] Zhou H, Long B, Cao BG. $H\infty$ robust controller for electric bicycles. In Proceedings of Workshop on Power Electronics and Intelligent Transportation System, Guangzhou, China, IEEE Computer Society, Piscataway, NJ, 2008, pp. 131–135.
[17] Hong BS, Lin TY, Su WJ. LPV modeling and synthesis for energy-efficient e-bikes. In Proceedings of 2009 CACS International Automatic Control Conference, Taipei, Taiwan, Chinese Automatic Control Society, Tainan, Taiwan, 2009.
[18] Abagnale C, Cardone M, Iodice P, Strano S, Terzo M, Vorraro G. Theoretical and Experimental Evaluation of a Chain Strength Measurement System for Pedelecs. Engineering Letters. 2014; 22: 3, pp. 102 – 108.
[19] Abagnale C, Cardone M, Iodice P, Strano S, Terzo M, Vorraro G. Analysis of a new measurement system of the chain strength for electrically assisted bicycles. In proceedings of the ASME 2014 12th Biennial Conference On Engineering Systems Design and Analysis – ESDA2014, Copenhagen, Denmark, 2014.
[20] Lomonova EA, Vandenput AJA, Rubacek J, d'Herripon B, Roovers G. Development of an improved electrically assisted bicycle. In Conf. Rec. IEEE IAS Annu. Meeting, 2002, vol. 1, pp. 384–389.
[21] Hsu RC, Member, IEEE, Liu GT, Chan DY. A Reinforcement-Learning-Based Assisted Power Management With QoR Provisioning for Human–Electric Hybrid Bicycle, IEEE Transactions on Industrial Electronics 2012; 59:8.