Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 101 (2016) 774 – 781

Energy Procedia

71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16 September 2016, Turin, Italy

Design and Development of an Innovative E-Bike

C. Abagnale[a], M. Cardone[b]*, P. Iodice[a], R. Marialto[c], S. Strano[a], M. Terzo[a], G. Vorraro

[a]*Department of Industrial Engineering, University of Naples Federico II, Napoli Italy*
[b]*Department of Chemical, Materials and Production Engineering, University of Naples Federico II, Napoli Italy*
[c]*Istituto Motori, CNR, Napoli Italy*

Abstract

A new model of power-assisted bicycle has been designed, set up and tested. The main innovative solutions for the pedelec prototype are described in the present paper: the electric motor position; the new mechanical transmission; the low cost measurement system of the driving torque; the special test rig. Differently from a common approach, in which the electric motor is located on one of the three hubs of the bicycle, the idea of the pedelec prototype consists of an electrical motor in the central position that, by means of a bevel gear, transmits the torque on the central hub. The other innovative solution is represented by the motion transmission from the motor to the pedal shaft, achieved by two different gearboxes: the first one is a planetary gearbox and the second one is a simple bevel gear. The pedelec prototype contains also a new low cost measurement system of the driving torque based on a strain gauge load cell located on one side of the rear wheel, between the hub and the frame. Moreover, a commercial cycling simulator has been suitably modified in order to properly install the different sensors for the measurement of the performance of the pedelec. The test rig is able to reproduce an aforethought route or paths acquired during road tests, to measure the performance of the e-bike in terms of instantaneous power and speed. The experimental test rig can simulate the resistant torque of a predetermined track and it aims to test and to optimize the control strategy available on the electronic control unit. The authors have also conducted an environmental analysis of the developed pedelec, in particular comparing the e-bike with a thermal moped, in terms of environmental impact.

Peer-review under responsibility of the Scientific Committee of ATI 2016.

Keywords: Electrically assisted bicycle, pedelec, pedal electric cycle

* Corresponding author. Prof. Massimo Cardone, Tel.: +39 081 7683675; fax: +39 081 2394165
E-mail address: massimo.cardone@unina.it

1876-6102
Peer-review under responsibility of the Scientific Committee of ATI 2016.
doi:10.1016/j.egypro.2016.11.098

1. Introduction

The large use of the travelling vehicles has increased the problems connected to the air quality and to the use of petroleum [1, 2]. The human sensibility for the energetic and environmental problems is encouraging the research in alternative solutions for the automotive field, as multiple-fueling, hybridization and electrification. At the same time, particularly as concerns urban areas, new standards have imposed substantial modifications in the mobility. In this context, a vehicle as the electrically assisted bike [3 – 5] can be considered a promising alternative vehicle for both personal mobility and goods delivery, especially for small and medium distances: an assisted bike is able to move with an average speed equal to the typical one of the town traffic but it requires energy for its mobility that is very close to the necessary energy for the displacement of the transported people.

The electrically assisted bikes are normally powered by rechargeable battery, and their driving performance is influenced by battery capacity, motor power, road types, operation weight, control, and, particularly, by the management of the assisted power. A classification of the electrically assisted bikes can be based on two categories: a first kind is represented by a pure electric bike [6 - 8], which integrates electric motor into bicycle frame or wheels, and it is driven by motor force just using a handlebar throttle; a second kind is a power-assisted bicycle, or called pedelec [9, 10] hereafter, which is a human–electric hybrid bicycle that supports the rider with electric power only when the rider is pedaling. The pedelecs are characterized by a driving torque due to both an electric motor torque and a rider one. Consequently, the management of the assistance torque is of particular interest in order to reach the desired performances in terms of driveability and comfort.

The present paper deals with the activity carried out on a prototype of an innovative power-assisted bicycle [11-19], designed at the Department of Industrial Engineering of the University of Naples Federico II: a pedelec characterized by an innovative layout of the electrical assistance and a new low cost measurement system of the total driving torque (rider torque + electrical motor torque).

The paper, that can be considered a synthesis of a wide activity including design, modelling, control and testing, is organized as follows: Section 2 presents the new pedelec, with its main innovative solutions; Section 3 describes the system modeling and control; the test rig suitably set up is detailed in Section 4; the results are illustrated in Section 5. Finally, Section 6 contains the conclusions and the future developments.

2. The Pedelec Prototype

A prototype of an innovative power-assisted bicycle has been adopted for the research activity. The new vehicle can be classified as a power-assisted bicycle, or pedelec [9, 10]: it is a human–electric hybrid bicycle that supports the rider with electric power only when the rider is pedaling. The developed pedelec presents some innovative solutions, resumed in three main aspects, as follows.

2.1. The central motor

Fig. 1 shows a photo of the pedelec prototype [11-13], where it is possible to note the electric motor in the central position. In fact, differently from a common approach, in which the electric motor is located on one of the three hubs of the bicycle, a basic idea of the pedelec prototype consists of an electrical motor that, by means of a bevel gear, transmits the torque on the central hub.

Fig. 1. Pedelec prototype

2.2. The new mechanical transmission

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. Fig. 2 shows a scheme of the second gearbox location. Derailleur gears are adopted in the pedelec drivetrain. The gear ratio depends on the ratio of the number of teeth on the rear sprocket to the number of teeth on the chain ring (equal to 39). The available gear ratios are listed in Table 1.

Table 1. Pedelec gear ratios

Number of teeth	Gear	Ratio
28	1	0.718
24	2	0.615
21	3	0.538
18	4	0.462
16	5	0.410
14	6	0.359

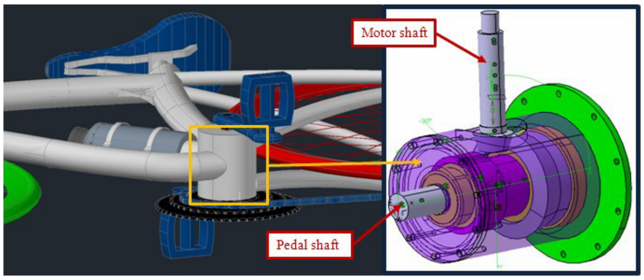

Fig. 2. Mechanical transmission between the motor shaft and the pedal shaft

2.3. The new measurement system

As concerns the measurements realized on the commercial pedelecs, they typically depend on the kind of control. Particularly, as regards the feedback controller, the rider torque is often required. Indeed, in this kind of controlled assisted bicycles, the contribution to the traction force of the vehicle by the electric motor can be made proportional to the contribution of the rider. For instance, the motor could be controlled in order to double the effort made by the cyclist. Moreover, the distribution between the motor power and the human power can further be controlled as function of other informations (speed, different assistance modes selected by the user). With reference to the measurements of the rider torque, two different devices are often employed. A first measurement system consists of a torsiometer mounted on the pedal hub [20]. Instead, a second device is based on a Hall effect sensor useful to measure the chain strength and located between the rear wheel hub and the frame [21].

The pedelec prototype contains a new low cost measurement system of the driving torque based on a strain gauge load cell located on one side of the rear wheel, between the hub and the frame (Fig. 3). On the other side of the wheel, a hinge constraint has been adopted in order to allow rotation in a plane parallel to the road surface. The strain gauge load cell is linked to the frame and to the hub by means of three hinges (A, B and C in Figure 3), in order to make the load applied to the load cell as close as possible to the chain strength.

The new measurement system, whose validation is the object of papers by the same authors [11-13], aims to know the chain strength and consequently, known the radius of the central crown, the total torque applied to the central hub and due to the contribution of both the electric motor and the rider.

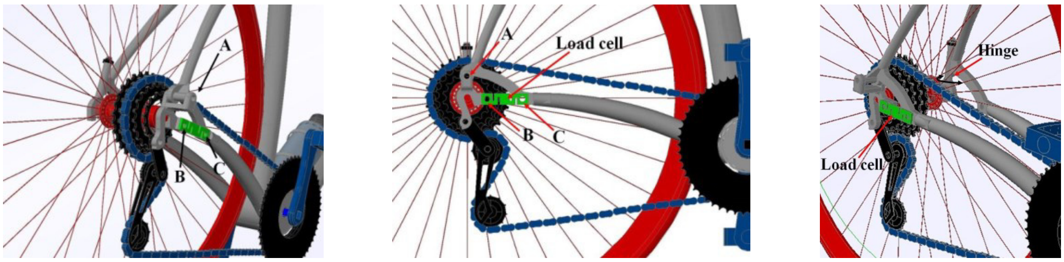

Fig. 3. Detail of the measurement system

3. System Modelling and Controller Design

In a human–electric hybrid bicycle that supports the rider with electric power only when the rider is pedalling, the management of the assistance torque (due to both an electric motor torque and a rider one) is of particular interest in order to reach the desired performances in terms of driveability and comfort. The procedure followed in the pedelec control, differently from the common approaches available in literature [22-28], is based on an optimal control of the assistance torque. The system model is based on the longitudinal vehicle dynamics and on the electrical motor one: the pedelec dynamics can be expressed as a combination of the bicycle longitudinal dynamics and the electric motor dynamics (Fig. 4).

The model has been derived and employed for the synthesis of an optimal control of the assistance torque. Moreover, an additional integral state has been adopted to make zero the tracking error in steady state conditions. The optimal pedelec torque control (OPTC) proposed control method is based on a torque control designed via an optimal approach to achieve multi-objective performances regarding the external disturbance input, control signal magnitude, and velocity tracking error. The performance of the methodology has been evaluated applying the proposed control to a model of the pedelec prototype, characterized by the measurement of the total torque (rider torque and electric motor one) employed as feedback for the control. To this aim, a mathematical model of the bicycle, equipped with the electric motor, has been developed, object of papers by the same authors [14, 16, 17]. The equations of the model (a second order nonlinear system that constitutes the basis for the controller synthesis) have been formulated representing the combined dynamic model of the whole system including the bicycle and the electric motor. The full system dynamics has been used for the power-assistance controller design. The OPTC consists in a pedelec torque control in which the input is the voltage to the electric motor and the measurements are the total torque T_{mis}, the motor angular velocity and the motor current. The gradient resistance accounts for a major part of the environmental disturbance, consequently, the nonlinear aerodynamic drag force is usually negligible in low speed riding and mild head wind condition. For this reason, the linear model of the whole system, constituted by the electric motor and the bike, has been obtained neglecting the aerodynamic resistance force. This unmodelled phenomenon can be compensated thanks to the robustness of the controller with respect to disturbances and model uncertainties. The scheme of the linearized model is reported in Fig. 5.

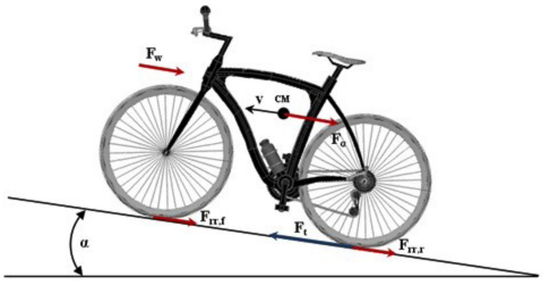

Fig. 4. Longitudinal components of forces acting on the pedelec

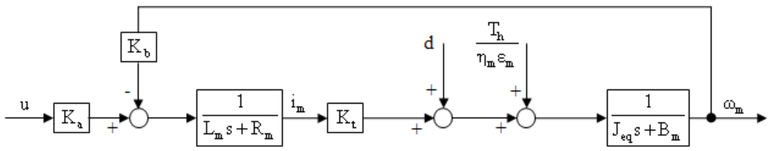

Fig. 5. Block diagram of the linearized pedelec model.

The state feedback OPTC design has been accomplished in order to minimize a weighted squared state error and control effort. The controller strategy consists in finding the input voltage to the electric motor in order to follow a target torque proportional to the actual rider one. To this aim, the total torque measurement from the novel torque sensor must be elaborated in order to obtain the reference motor current.The controller effectiveness is influenced by parameters that can vary, such as the total mass, the transmission ratio, etc. Also unmodelled phenomena could affect the performance of the controller. The feedback action of the optimal control guarantees stability and robustness in presence of limited variations of the controller parameters and unmodelled effects. This feature is typical of the feedback controller. Moreover, the additional control action, based on the integral of the current error, provides an improvement of the controller robustness. The feedback for the control is constituted by a new measurement system of the driving torque that characterizes the proposed bicycle. The optimal controller, developed starting from the linearized model, has been tested on the full nonlinear pedelec model.

3.1. Performance Evaluation

In order to evaluate the performances of the proposed approach, simulations have been carried out, modelling the human controller as a proportional-integral action finalized to track a desired velocity.

The performances have been compared with the ones referred to a traditional assistance approach and the results demonstrate that the proposed approach provides improvements in terms of riding comfort and energy employment.

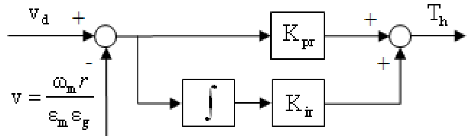

Fig. 6. Block diagram of the rider action.

The tracking performances and the disturbance rejection capability have been tested in simulation, employing a rider action modelled as a velocity controller based on a proportional-integral action. In the simulation study, a rider, that aims to follow a desired velocity, has been considered: the chosen rider is a young man. So, the action provided by the rider has been modelled as a torque dependent on the actual pedelec velocity and the desired one, by means of a proportional and an integral action. Fig. 6 shows a schematic diagram of the rider action. The rider coefficients K_{pr} and K_{ir} have been chosen in order to simulate the reaction time of the rider to the velocity response. A slope profile for testing the controller has been adopted. The desired pedelec velocity, imposed by the rider, has been fixed to 5 km/h. Different test cases have been considered for the control verification:

- In the first case, the OPTC has been evaluated considering the nominal vehicle parameters.
- The influences of the total vehicle mass and the rear gear ratio on the OPTC performance have been investigated in the second and the third case, respectively.
- In the fourth case, the comparison between the OPTC results with those obtained with a classical pedelec control system has been performed.

The results highlight that the proposed approach provides reduced tracking errors and good robustness, moreover, it performs better than classical pedelec assistance systems [19].

4. Test Rig and Measurement System

The experimental test rig has been realized starting from a commercial cycling simulator provided by ELITE srl (Fig. 7). The commercial cycling simulator has been suitably modified in order to properly install the different sensors for the measurement of the performance of the pedelec [18].

Figure 7. Detail of the cycling simulator.

Different paths can be simulated by means of the control software that manages the cycling simulator. The path can be realized in different ways, assigning one of the following relationships:

- power – time;
- slope – time;
- slope – distance;
- GPS data.

The motor driver used to perform the experimental tests implements a sensorless control algorithm and it determines when to commutate the motor drive voltages by sensing the BEMF voltage on an undriven motor terminal during one of the drive phases. The driver power rating is 250W on 36V nominal voltage with maximum current limited by hw at 7A and 20kHz PWM switching frequency. The control stage is based on a dsPIC DSC 16 bit microcontroller while the power stage is based on TI-DRV8332 integrated three phase motor drivers with an advanced protection system. The available measurements on the test rig are:

- the rear wheel angular velocity (by a magnetic pickup installed on the wheel with one pulse per revolution)
- the motor angular velocity (by three Hall effect sensors)
- the pedal shaft angular velocity (by a magnetic pickup installed on the pedal gear with five pulses per revolution)
- the motor current (by Hall effect sensor)
- chain strength (by a strain gauge load cell).

The experimental data have been acquired by a DS1103 real-time board equipped with a 16-bit A/D and D/A converter.

4.1. Experimental Tests

Preliminary experimental tests have involved the numerical relationship between the torque applied to the pedal shaft and the chain strength measurement. In this way, it is possible to adopt the chain strength sensor as a pedal shaft torque sensor.

The application of a known load F_p in correspondence of the pedals (Fig. 8) determines a known value of the pedal shaft torque: this value is correlated to the chain strength measurement. The longitudinal tire-road force generated by the pedal torque is balanced by the constraint due to the load cell.

Figure 8. Experimental setup for the estimation of the torque acting on the pedal starting from the chain strength sensor.

The experimental results are shown in Fig. 9, where the measured chain strengths (called F_s) and the known torques applied to the pedal shaft are reported for all the rear gear ratios. The curves reported in Fig. 9 have been implemented in the measurement system, in order to estimate the torque applied to the pedal shaft from the chain strength measurement. In this way, it is possible to estimate the power at the central hub starting from the applied torque and the pedal angular velocity.

Two experimental tests have been performed, in order to analyze the pedelec dynamics for a real urban riding. To this aim, the test rig has been adopted to simulate two different on-road test tracks (EP1 and EP2), characterized by the same origin and destination (and then the same cumulated climbing), but by different elevation profiles versus distance. The total distance of the two trips amounts to 1.8 km for EP1 and to 2.2 km for EP2. The altitude profiles, measured against distance, are reported for the two test tracks in Fig. 10.

For both experiments, all the available measurements have been acquired and some of them have been compared with the ones provided by the training system software.

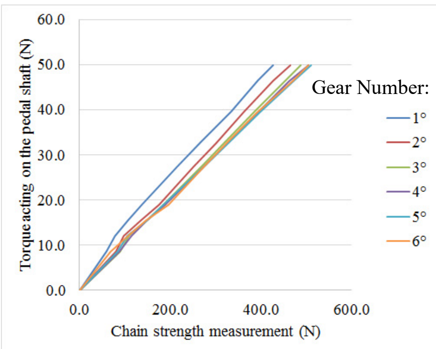

Figure 9. Results of the chain strenght sensor characterization

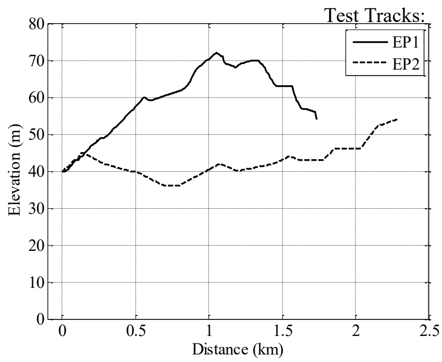

Figure 10. Altitude profiles versus distance for itineraries

The authors [12-15] have evaluated the pedelec velocity acquired against the travelled distance for both the trips, the instantaneous values of the gear ratios measured against the distance for the two itinerary, the pertinent profiles against the distance travelled, the measured motor angular velocities for both experiments.

4.2. Energy Analysis

Fig. 11 shows the values of the electric power obtained by multiplying the input motor current for the battery voltage (36 V). The values of the total power, instead, are calculated by the measurements of the chain strength and the pedal shaft angular velocity. These results have been reached [12-15] starting from the evaluation of the motor current values against the distance (values acquired by a hall effect sensor positioned downstream of the battery), considering the chain strength versus distance and the overall power and the electric power acquired versus distance, for the two itineraries.

In Fig. 11 and Fig. 12, the energies against the distance are obtained, for the two test tracks, by integration of the instantaneous electric power and the total power on the overall distance. By observing these two figures, it is clear that, while the electric energy for the two itineraries is very similar, the total energy required by the itinerary EP2 is higher than the other one. This is due to the higher distance of the itinerary EP2 that affects mostly the power to exceed the air strength and the power required to overcome the rolling resistances.

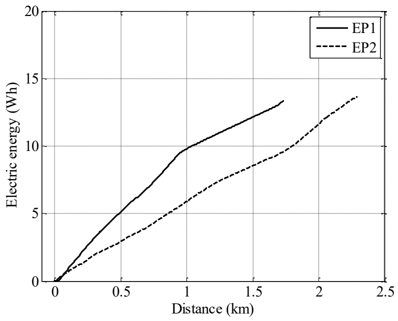

Fig. 11. Electric energy versus distance for itineraries EP1 and EP2

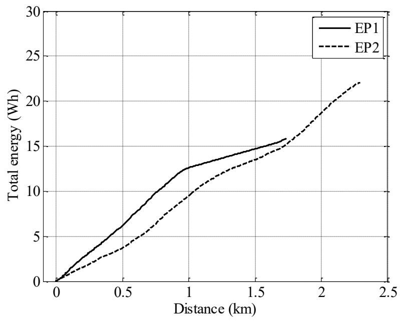

Fig. 12. Total energy versus distance for itineraries EP1 and EP2

5. Conclusions

The present paper deals with a wide activity carried out on a prototype of an innovative power-assisted bicycle.

After the design and the modeling of the vehicle characterized by some innovative solutions, the control has been implemented and testing on a suitable test rig has been carried out. The feedback for the control is constituted by a new measurement system of the driving torque that characterizes the proposed bicycle. The results highlight that the proposed approach provides reduced tracking errors and good robustness, moreover, it performs better than classical pedelec assistance systems.

The preliminary tests have been useful for the appraisal of power and energy requests of a pedelec under real driving conditions. The experimental test rig has simulated the resistant torque of these predetermined tracks in order to test and to optimize the control strategy available on the electronic control unit. In these conditions, it has been possible to measure the performance of the e-bike in terms of instantaneous power and speed versus distance, by the installed sensors and data acquisition system.

The experimental results have allowed to compare the total energy and the electric one for both the tracks, so, individualizing the optimum trip.

This study, then, has provided several results and guidelines that can assist for such improvements in the performance of electric bicycles. Future developments will concern the design of several control strategies by means of a hardware in the loop procedure.

Acknowledgements

This research has been financially supported by MIUR (Ministero Istruzione Università e Ricerca) under the grant named PON04a3_00408 "Bicicli e Tricicli elettrici a pedalata assistita di nuova generazione".

References

[1] T. Onoda and T. Gueret, *Fuel efficient road vehicle non-engine components: Potential saving and policy recommendations*, Int. Energy Agency Inf. Paper, 10 (2007), pp. 1–24.
[2] Iodice P, Senatore A. *Appraisal of pollutant emissions and air quality state in a critical Italian region: Methods and results*. Environmental Progress and Sustainable Energy 2015;34:1497-1505
[3] H. Seki, K. Ishihara, and S. Tadakuma, *Novel regenerative braking control of electric power-assisted wheelchair for safety downhill road driving*, IEEE Trans. Ind. Electron., 56 (5), (2009), pp. 1393–1400.
[4] C. C. Tsai, H. C. Huang, and S. C. Lin, *Adaptive neural network control of a self-balancing two-wheeled scooter*, IEEE Trans. Ind. Electron., 57 (4) (2010), pp. 1420–1428.
[5] A. Emadi, Y. J. Lee, and K. Rajashekara, *Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles*, IEEE Trans. Ind. Electron., 55 (6) (2008), pp. 2237–2245.
[6] P. Fairley, *China's cyclists take charge: Electric bicycles are selling by the millions despite efforts to ban them*, IEEE Spectr., 42 (6) (2005), pp. 54–59.
[7] N. Somchaiwong and W. Ponglangka, *Regenerative power control for electric bicycle*, in *Proc. IEEE Int. Joint Conf. SICE-ICASE*, 2006, pp. 4362–4365.
[8] M. J. Yang, H. L. Jhou, B. Y. Ma, and K. K. Shyu, *A cost-effective method of electric brake with energy regeneration for electric vehicles*, *IEEE Trans. Ind. Electron.*, 56 (6) (2009) pp. 2203–2212.
[9] D. Schneider, *Easy rider: Convert your bicycle to a human–electric hybrid*, IEEE Spectr., 46 (9) (2009), pp. 26–27.
[10] W. Du, D. Zhang, and X. Zhao, *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] C. Abagnale, M. Cardone, P. Iodice, S. Strano, M. Terzo, G. Vorraro, Analysis of a New Measurement System of the Chain Strength for Electrically Assisted Bicycles, Proc. of the ASME 12th Biennial Conference on Engineering Systems Design and Analysis (ESDA2014), ESDA2014-20364, Vol. 1, Copenhagen, Denmark, June 25–27, 2014.
[12] P. Iodice, C. Abagnale, M. Cardone, S. Strano, M. Terzo, G. Vorraro, Performance Evaluation and Environmental Analysis of an Electrically Assisted Bicycle Under Real Driving Conditions, Proc. of the ASME 12th Biennial Conference on Engineering Systems Design and Analysis (ESDA2014), ESDA2014-20438, Vol. 1, Copenhagen, Denmark, June 25–27, 2014.
[13] C. Abagnale, M. Cardone, P. Iodice, S. Strano, M. Terzo, G. Vorraro, Theoretical and Experimental Evaluation of a Chain Strength Measurement System for Pedelecs. Engineering Letters , 22 (3) (2014), pp. 102 – 108.
[14] C. Abagnale, M. Cardone, P. Iodice, S. Strano, M. Terzo, and G. Vorraro, Derivation and Validation of a Mathematical Model for a Novel Electric Bicycle, Lecture Notes in Engineering and Computer Science: Proceedings of The World Congress on Engineering 2015, 1-3 July, 2015, London, U.K., pp. 808-813.
[15] C. Abagnale, M. Cardone, P. Iodice, S. Strano, M. Terzo, G. Vorraro, Power requirements and environmental impact of a pedelec. A case study based on real-life applications, Environmental Impact Assessment Review, 53 (7) (2015), pp. 1–7, doi:10.1016/j.eiar.2015.02.003.
[16] C. Abagnale, M. Cardone, P. Iodice, S. Strano, M. Terzo, G. Vorraro, Model-based control for an innovative power-assisted bicycle, Energy Procedia, 81 (2015), pp. 606 – 617
[17] C. Abagnale, M. Cardone, P. Iodice, S. Strano, M. Terzo, G. Vorraro, A dynamic model for the performance and environmental analysis of an innovative e-bike, Energy Procedia, 81 (2015), pp. 618 – 627
[18] C. Abagnale, M. Cardone, P. Iodice, S. Strano, M. Terzo, G. Vorraro, Design and Development of a Test Rig for E-bike Performance Evaluation, Proc. of the 12th International Conference on Engines & Vehicles, Capri, Italy, September, 2015
[19] M. Cardone, S. Strano, M. Terzo, Optimal power-assistance system for a new pedelec model. Proc. IMechE, Part C: Journal of Mechanical Engineering Science, DOI: 10.1177/0954406215604657, in press.
[20] X-CELL RT, http://www.thun.de/en/products/sensor-technology/.
[21] TMM sensor, http://www.idbike.com/tmm-powermanagement.htm.
[22] T. Tanaka, and T. Murakami, *A Study on Straight-Line Tracking and Posture Control in Electric Bicycle*, IEEE Trans. Industrial Electronics, 56 (2009), pp. 159–168.
[23] C.L. Hwang, H.M. Wu and C.L. Shih, *Fuzzy Sliding-Mode Underactuated Control for Autonomous Dynamic Balance of an Electrical Bicycle*, IEEE Trans. Control Systems Technology, 17 (2009), pp. 658–670.
[24] P.H. Chen, *Intelligent application: ELEBIKE Fuzzy Control: Part 1*, in *Proceedings of the Seventh International Conference Machine Learning and Cybernetics*, Kunming, China, 2008, pp. 3581–3585.
[25] C.Y. Liang, W.H. Lin, and B. Chang, *Applying Fuzzy Control to an Electric Bicycle*, in *Proceedings of First International Conference on Innovative Computing, Information and Control*, Beijing, China, 2006, pp.513-516.
[26] Q. Zheng and M. Tomizuka, *A disturbance observer approach to detecting and rejecting narrow-band disturbances in hard disk drives*, in *Proceedings of the AMC 2008*, Trento, Italy,2008, pp. 254-259.
[27] M.T. White, M. Tomizuka, and C. Smith, *Improved track following in magnetic disk drives using a disturbance observer*, IEEE/ASME Transactions on Mechatronics, 5 (2000), pp. 3 – 11.
[28] S.B. Chang, P.C. Chen, H.S. Chuang, C.C. Hsiao, *Velocity control with disturbance observer for pedal-assisted electric bikes*, Vehicle System Dynamics, 50 (2012), pp. 1631 – 1651.