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Electric System Design for Electric Reverse Tricycle for the Elderly

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Abstract

This paper suggests electric reverse tricycle that has the Ackerman-Jantoud steering structure and the power assist system for the elderly. First of all, the required power point of view, driving power performance analysis of electric reverse tricycle is discussed for selecting diving system. for selecting motor and battery. After that system configuration for major electric components such as motor, inverter, battery and high level controller is described. And then, the communication system design among battery management system, inverter, display device and high level controller is discussed. Last of all, hardware and software design of the power assist system is fully described. The performance of the electric reverse tricycle is also described and evaluated experimentally.

Keywords: Power Assist System, Electric Reverse Tricycle, Electric Control Unit, Mobility

1 Introduction

It is expected that the modern society is rapidly shifting into aging society due to a prolonged average life span and a low birth rate. According to this tendency retired older generations who have financial power are also getting increase. At the same time, global electric bicycle market is rapidly increasing because of eco-friendly and energy saving policy of the government and leisure and sports industry expansion[1] - [2].

According to these tendency, many researchers around the world had suggested electric bicycle system and its control methods. Kazuyoshi H. et al had suggested power assist control strategy from energy efficient point of view[3]. E.A. Lomonova et al had suggested various motor design methods for improved electrically assisted bicycle[4]. Hidenori Y. et al are described environmental adaptive control algorithm from the control point of view[5]. Stone C. et al had suggested dynamic power management method for power assisted electric bicycle[6]. However their researches are limited to develop power assist control strategy or to save power strategy.

Therefore it is needed to develop safe and convenient electric bicycles that satisfies their desire for the leisure and the health at the same time. To overcome limitations of past researches that have mainly focused on developing power assist and power saving strategy and to design more suitable electric bicycle and electric system for elderly, this paper suggests electric reverse tricycle that has the Ackerman-Jantoud steering structure and its electric system including CAN communication and power assist system.

This paper is organized as follows. In section 2, Ackermann-Jantoud steering structure is discussed first. Then, driving power performance analysis for selecting motor is described. After that, electric systems including battery, motor and ECU(Electric Control Unit)s including high level controller, BMS (Battery Management System) and inverter are described in section 4. In section 5, pedal assist system and speed control algorithm are discussed. The experimental results follow in section 6.

2 Steering Structure Design

Since balancing ability of the elderly is poor, we have designed reverse-tricycle. Since there are two wheels at the front of the bicycle, if both of the wheels were turned by the same amount when bicycle turns corner, the slip is occurred at the inside wheel and it creates unwanted heat and power loss. These phenomena can be minimized by applying Ackermann-Jantoud steering system which turns the inside wheel at a larger angle than the outside wheel at cornering.[7]. To achieve this, we have designed Ackermann-Jantoud front steering wheel structure as follows. 1) Making reverse triangle that has three points those are center axis of two front wheel and center axes of back wheel. 2) Making parallelogram linkage that constraints two front wheels by connecting front two vertexes of the reverse triangle. 3) Verifying Ackermann-Jantoud steering geometry by moving the steering pivot points inward so as to lie on a line drawn between the front constraint points and on a line drawn of the rear wheel center.

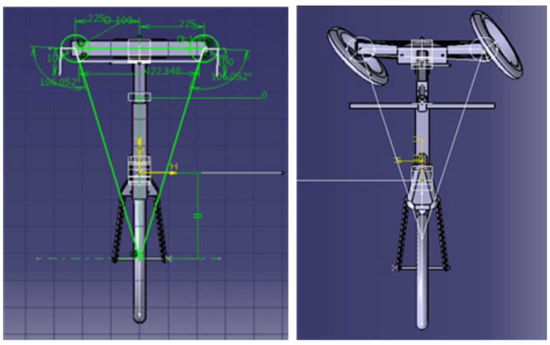

Figure 1: Ackerman-Jantoud Steering Structure Design

3 Driving Power Performance Analysis for Selecting Motor

The total road loads are defined sum of rolling resistance, air drag resistance and hill climbing resistance[8]. The Regenerative energy from rapid deceleration and hill descent is ignored.

$$R_{RL} = \mu_r W + \frac{1}{2}\rho A C_d (v_w + v_g)^2 + W \sin\theta \quad (1)$$

where, R_{RL} is total road loads, μ_r is rolling resistance coefficient, W is the total mass of the bicycle, rider and load being carried, A is the frontal area, C_d is the coefficient of air drag, ρ is the density of air , v_w is the speed of wind, v_g is the ground speed, respectively.
Traction force(F_t) and bicycle speed(V) by electric motor can be expressed as follows:

$$F_t = \frac{T_m i_g \eta_o}{r} \quad (2)$$

$$V = \frac{\pi \omega_m r}{30 i_g} \quad (3)$$

where, T_m is the motor torque, i_g is the gear ratio, η_o is the total efficiency of driving power transfer, r is the radius of the tire and ω_m is the angular velocity of the motor, respectively.
Since electric reverse tricycle can not accelerate when traction power equals to running resistance, maximum speed of the electric reverse tricycle can be obtained by eq. 4:

$$V_{\max} = \sqrt{\frac{2}{\rho A C_d}\left(\frac{T_m i_g \eta_o}{r} - \mu_r W - W \sin\theta\right)} \quad (4)$$

The grade ability(G) that refers to how steep a grade the vehicle can climb can be easily obtained by relationship between traction force and running resistance as eq. 5.

$$G = 100(\sin^{-1}(\frac{1}{W}(F_t - \mu_r W - \frac{1}{2}\rho A C_d V^2)) \quad (5)$$

Acceleration performance is expressed by acceleration time and moving distance from initial position ($v = 0$) to specific speed. Acceleration can be expressed by Newton's second law :

$$a = \frac{F_g}{W_e/g} = \frac{F_t - F_r - F_a}{W_e/g} \quad (6)$$

where, a is the electric reverse tricycle acceleration, W_e is the equivalent inertia weight which is defined as $W_e = (1 + 0.04 + 0.0025 i_g^2)W$ and g is the gravity acceleration, respectively.
The power of electric motor that satisfies driving performance of the electric tricycle is needed to calculate for selecting electric motor. The power of the electric motor is defined by product of the force of electric motor and speed of the electric tricycle.

$$P_m = F_m \omega_m \quad (7)$$

where, P_m is the power of electric motor, F_m is the Force of the electric motor and ω_m is the angular velocity of the electric motor, respectively.
Since loss by air drag resistance is so small as to be negligible in constant torque region, it is possible to assume that real traction force at the tier is constant and the acceleration in constant torque region can be also assumed constant. And in constant torque region, the torque of the motor equals to sum of traction force that is transferred to the ground and running resistance loss.

$$T_m = \frac{r}{i_g \eta_o} \times \frac{v_b w_e}{g t_b} + \mu W + \frac{1}{2}\rho A C_d v_b^2 \quad (8)$$

Therefore required motor power can be obtained from eq. 7 and eq. 8.

$$P_m = \frac{T_m i_g \eta_o v_b}{r} \quad (9)$$

4 System Design

4.1 Electric System Design

The electric systems is consisted of inverter, battery management system(BMS) and high level controller. The high level controller monitors all of the statuses (SOC, over or under voltage, current rpm, fault information and so on) from inverter and BMS. And it also sends torque reference to the inverter automatically by power assist system (PAS) algorithm. The inverter drives motor according to torque reference. The BMS monitors statuses of the battery and broadcasts battery status information via CAN communication. System configuration is shown in Fig. 3.

4.1.1 Motor Selection

We have defined the specification of the electric tricycle as table 1 and developed motor performance estimation software using visual studio 2008 as shown in Fig. 2 based on theories and equations those are described in section 2. Developed software is designed to calculate motor power and RPM automatically by pre-defined motor parameters such as mass of bicycle, motor efficiency, radius of tire and so on.

Table 1: Target Specification of the E-Tricycle

List	Value
Max Moving Distance	40km
Max Moving Distance per day	20km
Mass of E-Tricycle	30kg
Mass of Driver	80kg
Mass of Extra	20kg
Max Speed (Motor Only)	15km/h
Max speed (Motor + Driver)	30km/h

As a result, the BLDC motor with 370W and 250RPM is selected as shown in table 2.

4.1.2 Battery Selection

The output voltage and current of the battery is selected by 36V that is input voltage of the motor and 10Ah for considering output power of motor that is 350W. The li-ion battery of the Samsung SDI, "ICR18650-22" is selected as the battery cell and the specification of the battery shown in table 3.

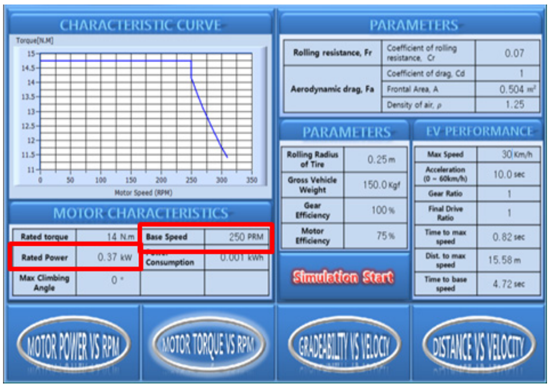

Figure 2: Selecting Motor using predefined e-Tricycle Parameter

Table 2: Motor Specification

Lists	Value
Voltage	36V
Wheels Size	20inch
RPM	255
Rated Current	<13A
Efficiency	<75 %

Table 3: Battery Specification

Item	Value
Typical Capacity	2150mAh (0.2C, 2.75V discharge)
Minimum Capacity	2050mAh (0.2C, 2.75V discharge)
Charging Voltage	4.2V0.05 V
Nominal Voltage	3.62V (1C discharge)
Charging Method	CC-CV
Charging Current	Standard charge: 1075mA Rapid charge : 2150mA
Charging Time	Standard charge: 3hours Rapid charge : 2.5hours
Max. Charge Current	2150mA
Max. Discharge Current	10A (Continuous discharge)

4.2 Electric Control Unit Design

The electric reverse tricycle has four different electric control units(ECU): Display device for display status of the reverse e-tricycle, Inverter for motor control, High Level Controller (HLC) for managing whole system, and Battery Management System (BMS) for managing battery. The HLC is designed to get sensor value from PAS (Power Assist System) sensor in real-time for driving motor depends on status of the driver and to send motor control command(torque or speed) to the inverter when driver needs power assist. The inverter is designed to get reference torque or speed from the HLS and to drive motor according to pre-defined driving profile. The BMS is designed to monitor and to share status

information of the battery and to protect battery from emergency situation such as over voltage, over current and so on.
Since there are many data to share among ECUs, communication method based on BUS is more capable than 1:1 communication in electric tricycle system. Therefore the CAN communication is selected to reduce complexity of wire harness and to increase robustness of communication. The electric system of the reverse e-tricycle is depicted in Fig. 3.

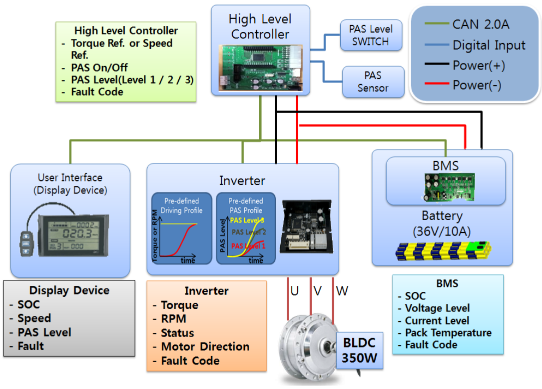

Figure 3: Electric System and Communication System Design

4.2.1 High Level Controller Design

The HLC is consisted of power management part, communication part and PAS(Power Assist System) sensor interface part and is used 8 bit MCU(Micro Control Unit) of the Atmel cooperation. Power management part has two DC-DC converters for converting input voltage(36V) to 5V, 3.3V that is operation voltage of the MCU. The communication part consists of serial communication(RS232) for debugging and CAN communication for sending motor control command to the inverter and getting all the status information of the inverter and the BMS. The external interrupt is used to interface PAS sensor. Developed HLC and hardware configuration of the HLC is shown in Fig. 4.

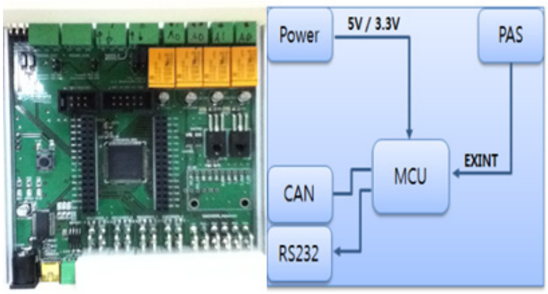

Figure 4: Developed HLC and H/W configuration of the HLC

4.2.2 Inverter Design

The inverter that is used to control BLDC motor is consisted of power part, motor control part, sensing part and communication part. Power part has two DC-DC converters for regulating 5V and 3.3V. Sensing part senses current that flows to the BLDC motor and interface hall sensors that is mounted in the BLDC motor. The CAN communication is applied to receive torque or rpm command from the HLC and to transmit status information of the motor. RS232 communication is also applied for configuring control parameter of the inverter. In motor control part, 6 FETs are used as switching device and gate driver is used to amplify output voltage of PWM to 36V that is operational voltage of the BLDC motor. Developed inverter and hardware configuration of the inverter is shown in Fig. 5.

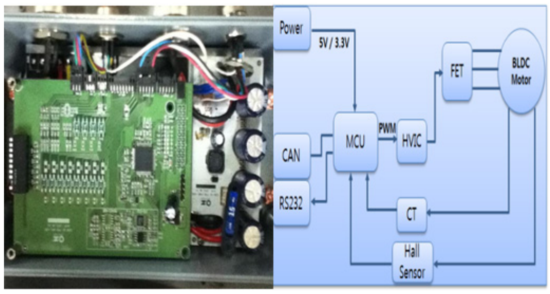

Figure 5: Developed inverter and H/W configuration of the inverter

4.2.3 Battery Management System Design

The BMS that monitors status of the battery and protects battery from emergency situation such as over voltage or over current is consisted of protection part, battery management and cell balancing part, communication part. The AVR of Atmel cooperation is used as a MCU and the bq77910A of TI cooperation is used for protecting battery from over voltage, short circuit and over current. The bq34z100 is also used for monitoring statuses of the battery such as SOC, voltage and current. The monitoring information is designed to transmit to the AVR via I2C communication. And the AVR is designed to transmit all the status information of the battery to the inverter or the HLC via CAN communication. Developed BMS and hardware configuration of the BMS is shown in Fig. 6.

5 Power Assist System

Since reverse electric tricycle is developed for elderly who has weak strength, the power assist system (PAS) is one of the important technology. We have used two types of magnetic sensors for pedal assist system. Inner bottom bracket type of magnetic sensor that has 32 pulse per cycle is used as pedal speed sensing and it is mounted on

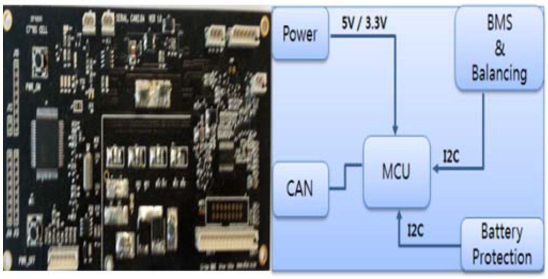

Figure 6: Developed BMS and H/W configuration of the BMS

the bottom bracket as shown in right side of fig 7. Outer bottom bracket type of magnetic sensor that has 12 pulse per cycle is uses as bicycle speed sensing and it is mounted on the rear wheel motor as shown in left side of fig. 7.

5.1 Pedal and Bicycle Speed Sensing

The output signal of the pedal and bicycle speed sensor are connected with external interrupt pin of the high level controller, and gives high(5V) or low(0V) signal when magnetic sensor passes magnetic continuously. Therefore if we count every positive transition position(high to low) in specific time, current pedaling and bicycle speed of electric reverse tricycle, v_p and v_b, are calculated as eq. 10 and eq. 11.

$$v_p = \frac{p_{c\_nop} \times 2\pi R_c \times 0.036}{p_{c\_ppr} \times t} \tag{10}$$

$$v_b = \frac{p_{b\_nop} \times 2\pi R_r \times 0.036}{p_{r\_ppr} \times t} \tag{11}$$

where P_{c_nop} is the number of pulse of the pedal speed sensor in specific time, R_c is the radius of the crank, and p_{c_ppr} is number of pulse of the pedal speed sensor per one revolution, P_{b_nop} is the number of pulse of the bicycle speed sensor in specific time, R_r is the radius of the rear wheel and p_{r_ppr} is number of pulse of the bicycle speed sensor per one revolution, respectively.

5.2 Power Assist Control Algorithm using Pedal and Bicycle Speed Sensor

Since we design power assist system operates when user starts pedalling at the beginning and climbs the steep hill, we use two pedal speed value and bicycle speed value as control variables. According to predefined speed of the reverse electric bicycle and pedal speed, when current speed of the reverse electric tricycle and pedal speed are lower than predefined speed of reverse electric tricycle and pedal and current pedal speed reference torque is increased and sends to the inverter via CAN communication by the HLC. And when current speed of the reverse electric tricycle is faster than predefined

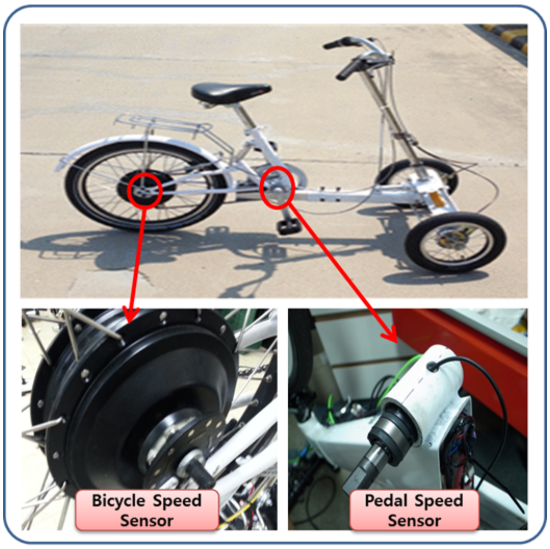

Figure 7: Pedal and Bicycle Speed Sensor Installation

reverse electric tricycle speed or pedaling speed is faster than predefined pedal speed, reference torque is decreased automatically and transmits to the inverter via CAN communication by the HLC. When the inverter receives torque command from the HLC, the inverter controls torque of the BLDC motor by PI controller with anti-windup as depicted in Fig. 8.

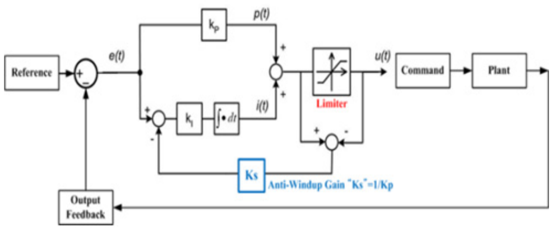

Figure 8: Block Diagram of the Torque Controller of the Inverter

6 Experimental Results

6.1 Lab Test Setup and Experimental Results

The lab test has performed using lab-test bench. Lab test bench is consisted of generator and load controller as shown in 9-(a). In load controller, PWM(Pulse Width Modulation) current controller is used for adjusting load and heat resistance is used to dissipate energy from load generator as shown in fig. 9-(b).

Fig. 10 shows lab test results. Since 350W BLDC motor is used as a driving system, we set maximum 10000mA as a reference current. We also did a experiment for testing pedal assist algorithm by changing pedaling speed. The experimental results shows that average current

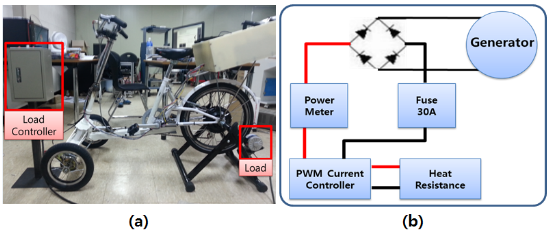

Figure 9: Lab Test Environment a) Lab Test Set-up b) Load Controller Block Diagram

control error is 58.8mA and 1.9 second is took when current reaches to the maximum output current(10A) from 0A as shown in fig. 10-(a). According to pedal and bicycle speed, power assist algorithm makes reference current well and controlled current follows reference current with average control error of 62.3mA as depicted in fig. 10-(b).

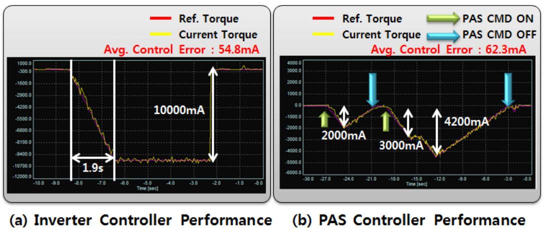

Figure 10: Experimental Results a) Control Performance of the Inverter Controller b) Control Performance of the PAS Controller

6.2 Riding Test in the Real Road and Experimental Result

Public road of the Korea Automotive Technology Institute Technology(KATECH) is selected as a real road test environment. Total test distance of the test road is set by 648m and two rising slopes and two falling slopes are included in the test environment as shown in fig. 11.

Figure 11: Test Envrionment

Fig. 12 depicts real road riding experimental results with power assisted system on real road test environment. The motor torque is increased by power assist algorithm automatically at the stating section, and rising slope sections (section B and D). Since the rising slope of the section D is more steeper than section B, more discharging current is used at section D than section B. And because of the power assist algorithm at the section B and D, pedaling speed of the bicycle is increased rapidly.

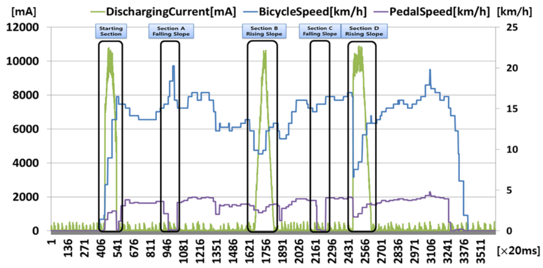

Figure 12: Riding Experimental Results with PAS Algorithm in Real Road Envionment

7 Conclusion

In this paper, electric reverse tricycle that has the Ackerman-Jantoud steering structure and the power assist system using two sensors is described for elderly who have weak balance ability and strength. According to the power analysis and its simulation results, electric component such as motor and battery are chosen. Electric control units such as BMS, inverter and high level controller that support CAN communication are developed. Under the given application, applying CAN communication instead of serial communication is very efficient solution with respect to reduce complexity of the electric wire harness and to increase robustness of the communication error. Especially, power assist algorithm and control logic is suggested in this paper. In this way, given system assists driving power when rider starts pedaling and climbing the steep hill automatically. With use of the test bench, suggested system could be tested and be verified its full performance safety. Finally, developed electric reverse tricycle is tested its mobility and driving assist system under real test environment and given test test scenario. With more advanced steering structure, electric system and driving assist control strategy, it can be expected that easier, safer and more comfortable electric bicycle is provided to the elderly.

Acknowledgments

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