Optimization of a low weight electronic differential for LEVs

- Efficient design for independent one axis two in-wheel engines -

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ABSTRACT:

It is presented a performance analysis of an Electronic Differential (ED) system designed for Light Electric Vehicles (LEVs). We have developed a test tricycle vehicle with one front steering wheel and two rear fixed units is a same axis with a brushless DC integrated in each of them. Each motor has an independent controller unit and a common Arduino electronic CPU based that can plan specific speeds for each wheels as curves are being traced.

Different implementations of sensors (input current/torque, steering angle and speed of the wheels) are discussed related to hardware complexity, and performance obtained based on speed level requirements and slipping on the traction wheels.

KEY WORDS: Electronic differential, light electric vehicle, microcontroller control, torque, sensor feedback

1. INTRODUCTION

Light Electric Vehicles (LEVs) are one of the most important alternatives to reach a sustainable urban mobility scenario. These are low weight vehicles (approx. in the same order as the total weight of its passengers or load). This allows a very low energy consumption and, therefore, a mobility efficiency superior to that achieved with conventional electric vehicles (1).

Nowadays the most used architecture for LEVs is the two-wheeled models as in electric bicycles or motorcycles. These vehicles have a single drive wheel and their motor control system are simple and low cost. However, they present 3 major drawbacks:

- High aerodynamic coefficient (with a negative impact on their energy efficiency)
- Driver's exposure to bad weather
- Low stability at low speeds

The 3 or 4 wheels enclosed body LEVs appear as an alternative that solve these drawbacks. They can also work on a single drive wheel, keeping simple and inexpensive, but still face a major drawback: a very low cornering stability that limits their maximum speed (2).

There are several hardware solutions to improve this stability in tricycles such as tilt-wheeled designs but the most common alternative to improve stability is to use a two front wheels motion system (3). In this case, they need to rotate at different speeds when changing direction with our vehicle. The use of a mechanical differential is widespread in most vehicles and even in some LEVs (4). The main problem of this solution is that they result very heavy and, consequently, are not suitable to be used in high efficient LEVS. In this case it is an advantage to implement an Electronic Differential (ED) system.

The main characteristics of these ED are:

- There is no mechanical link between the two wheels powered by an engine. Each of them is coupled to an electric motor that is independently controlled.
- The traction power is independently applied to each driving wheel.
- The ED simulates a differential lock while the front wheels are driving straight paths.

Even in the simplest form of implementation, a controller of these characteristics presents a level of complexity quite superior to any standard controller used in a single motor drive vehicle due to the synchronization requirements.

Several studies claim that a ED controller may require to work the measure the speed of each driving wheels, the current of each motor and/or the steering angle (5). Some sensors can be eliminated to gain simplicity and robustness at the expense of reducing functional features. A controller without wheel speed sensors is proposed in (6) and another controller without steering angle sensor nor speed sensors is proposed in (7). Both designs are applied to EVs driven with induction motors. This allows obtaining the advantages of higher reliability, low price and broad range of products and suppliers.

2. EXPERIMENTAL PROCEDURE

A very small weight control system has been developed based on a microcontroller platform implemented in a four-wheeled LEV with two independent engines placed on the two front units. This CPU can regulate the input power of these engines and sense all the variables introduced on the previous chapter. The selected processor is able to implement complex functions such as traction control and anti-lock wheel procedures.

Three different variables measurement systems have been integrated in different implementations developed to compare complexity and behaviors toward managing an optimized ED:

A.- Lecture of the current applied to each motor. The torque delivered by each motor is estimated as it is proportional to its input current (Analog)

B.- Hall effect sensors. This lecture allows to calculate the rotation speed of the wheels without using a dedicated speed sensors (Analog).

C.- Position sensors is to measure the steering angle of each driving wheels (Analog)

2.1. Workplan

A laboratory test unit was developed to generate the basic architecture of the control system and to program and test the algorithms of the microcontroller to efficiently manage to control in a synchronized patter the two driving wheels. Different mechanical resistance applied to each wheel allow to simulate different trace driving conditions. See Figure 1.

Fig. 1 Laboratory development set for the ED unit.

Afterwards, a test vehicle driven with two independent brushless DC motors installed in the same axis of the vehicle and directly coupled to the two driving wheels has been generated (8).

The vehicle has been constructed over a common bicycle chassis integrating a rear platform to set the two driving wheels (figure 2), the electronic control and the ED and the battery is placed in the main frame of the bike. All the system had been characterized measuring all his fundamental parameters as the inductance of the engines (figure 3).

This configuration allows these motors to rotate at different speeds when the vehicle traces a curve.

- When driving straight forward, the two motors of the power train deliver the same torque rotating their wheels at equal speed and no differential control is executed
- When the steering system starts forcing the vehicle to trace a curve, the torque of each motor is modified to allow each wheel to spin at a different speed

The final architecture of the ED developed is presented in Figures 4 (schematic) and 5 (physical implementation). They include the basic elements describes in the literature (9) (10) along with the sensor described before.

An exhaustive evaluation test is proposed including low and high driving speeds that generates slipping conditions in the drive train wheels. The vehicle has been subjected to two scenarios where trajectory and current and speed data from the electric engines has been collected and analyzed (see figure 6):

- A circular path with the minimum radius allowed by the chassis of the vehicle that traces the outer wheel
- A slalom path route with alternative sharp changes in the vehicle´s direction

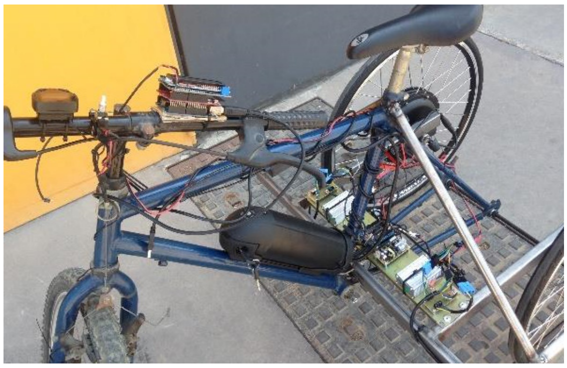

Fig. 2 Three-wheel LEV system generated reconditioning a common bicycle.

Fig. 3 Initial characterization of the engines of the tricycle.

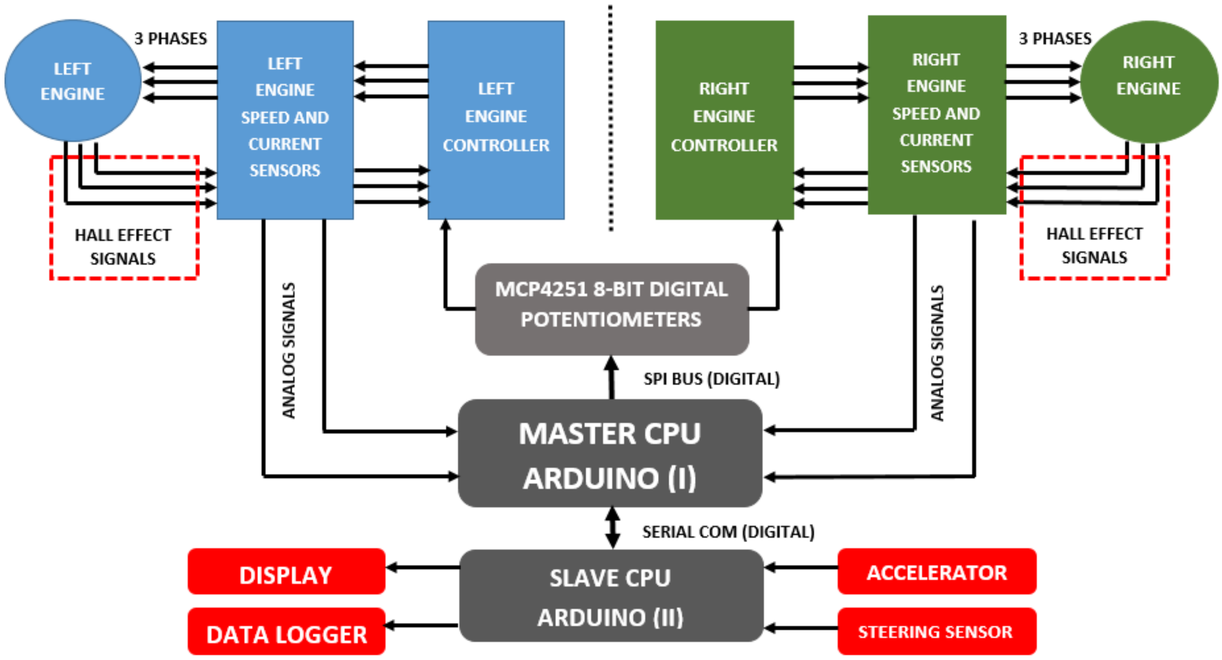

Fig. 4 Schematic of the ED unit and its relationship with sensor and the power units

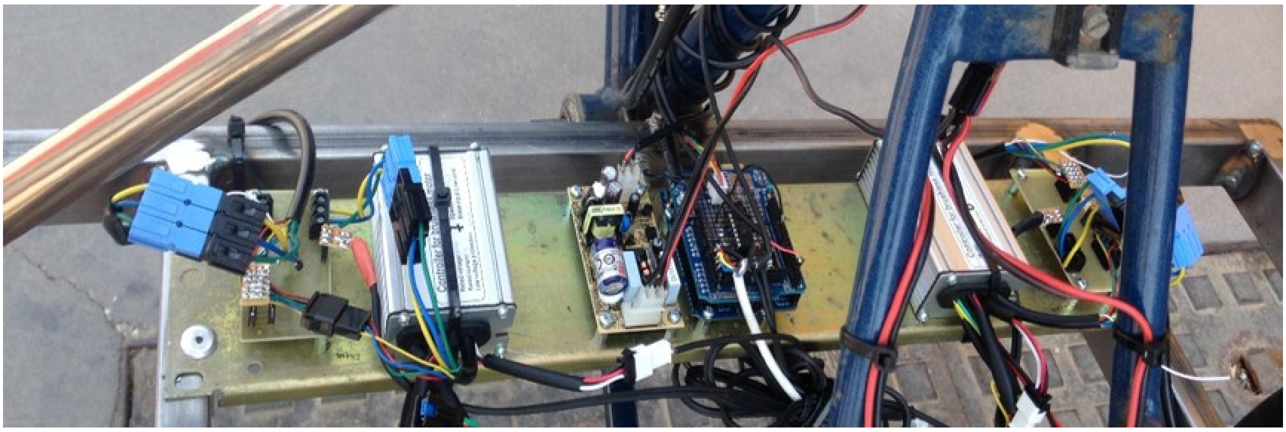

Fig. 5 Independent engine controllers and ED with the Arduino CPU. Each engine also present an input current sensor placed on the outside sides of the image

Fig. 6 Outdoor driving test procedure to evaluate different configurations of sensors.

Fig. 7 Visualization of the instantaneous measures in the system of the three variables under study.

Information of the working aspects of the ED can be observed while driving by the operator observing a LCD screen placed on the handlebar of the tricycle and can adjust the trace and speed according to this information while performing test or doing a normal use of the vehicle (See figure 7).

2.1. Traction control

The control of traction in one of the main variables in the optimization of the mode of operation of an LEV. This is one of the main causes of energy losses. The objective of the ED, in this case, is to detect if the slippage of any of the wheels occurs and act over it decreasing the torque exerted on the referend engine (11).

In a moving vehicle that is tracing a curve to the right of radius R and angle θ The distance traveled by each wheel in that curve is as follows (using the subscript 'L' to refer to the wheel on the left and 'R' for the unit placed on the right):

$X_R=2\pi R_R*\theta/360$

$X_L=2\pi R_L*\theta/360=2\pi*(R_R+d)*\theta/360$

Being 'd' the distance between both wheels. The linear speed of each wheel will be given by the quotient between the space traveled and the time used for it, which is the same as there is a common axis. We can gather the terms that do not depend on whether it is the inner or outer wheel in a factor k, leaving us the following expressions of the speed:

$V_R = X_R*t = 1/t*2\pi R_R*\theta/360=kR_R$

$V_L = X_L*t = 1/t*2\pi(R_R+d)*\theta/360=k*(R_R+d)$

$k = 2\pi\theta/(360*t)$

Relating both equations:

$V_L=(1+d/R_R)*V_R$

If the speed of the left wheel exceeds that value with respect to the right, it means that it is sliding, and therefore, it will be necessary to reduce the torque input from the CPU of the ED.

This information can be provided by an angular position sensor that measures the rotation of the handlebar of the tricycle. This sensor must be placed in the front wheel and the slave CPU will take the obligation of harvesting the data out of it. It is a delicate sensor, that need to be properly calibrated and that the vibrations or a shock in the vehicle may generate wrong data that generates malfunctions.

In the case of eliminating its presence, it will not be possible to know exactly the radius of the curve the vehicle is taking at any moment or to which side it is turning on.

However, we can estimate this information relating the speed of both rear wheels with the front one (in this case a single wheel, if it were a four-wheel vehicle, we would compare with the two that do not deal with traction) (12).

The maximum speed that the rear wheels can reach depending on the values of the front element is:

$Vm\acute{a}x = (R_F+d/2)/R_F*V_F = (1+d/2R_F)*V_F$

This value is maximized for the minimum turning radius that the front wheel can face.

Since it is known the separation distance of the rear wheels and the speed of the front wheel can be known by means of a sensor of the same type as those used for the motors, if we measure the minimum radius of rotation experimentally, we will obtain the maximum speed value that can reach the rear wheels with respect to the front without sliding.

It can be estimated that if any of the wheels exceeds this value at some point, it means that it has lost grip and is sliding, which will proceed to reduce the torque awarded to it.

3. RESULTS

The simplest ED control system depend on sensing only the variation of torque delivered to each wheel as it reduces the duty cycle of the control signal of the inner wheel motor and increase that of the outer wheel until the torque delivered by both motors returns to be equal to the set point set by the accelerator and the speed of the motors is adequate to trace the curve correctly.

When the trajectory of the vehicle becomes curve, the inner wheel speed (the left wheel in this case) is lower than the outer one (right one). On the other hand, the current signal remains practically identical for both motors, which means that the torque is the same. It has been also compared the theoretical speed ratio between both wheels to the experimental value, obtaining an error of 2.03%. This error is within the expected range, due to the difficulty of maintaining an exact radius during the entire trajectory.

At low speed (< 10 Km/k approx.), and even in sharp curves (not full circles), when there is no slipping on any of the wheels this basic ED architecture works properly and in a smooth way (See figure 10). However, in all the cases where it is not sensed the speed of the driving wheels abnormal situations, such as blocking or slipping of a wheel due to higher speeds or extremely sharp turns, cannot be detected in advance and, consequently, not solved properly (See figure 11). When some of these situations appears the previous detailed errors arise. They may result in an energy loss up to a 40% and in severe cases may generate an extreme loss of stability that can conduct to a turnover of the vehicle.

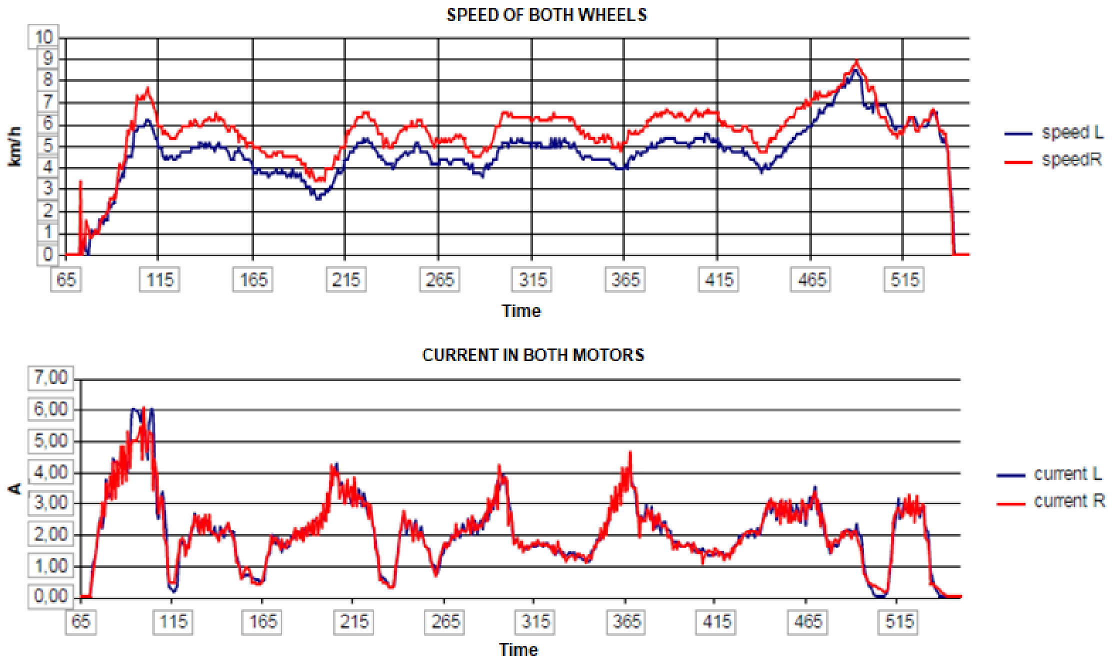

Figure 8. ED control results base exclusively on variation of torque feedback at an average 5 Km/h on a sloping circuit.

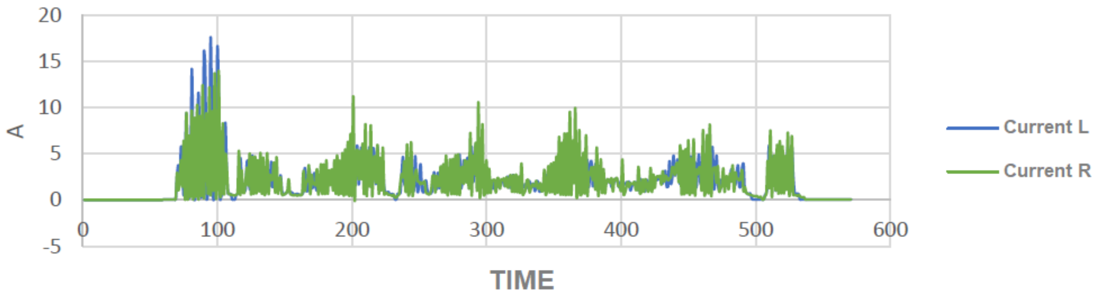

Figure 9. ED control results base exclusively on variation of torque feedback at an average 15 Km/h on a sloping circuit.

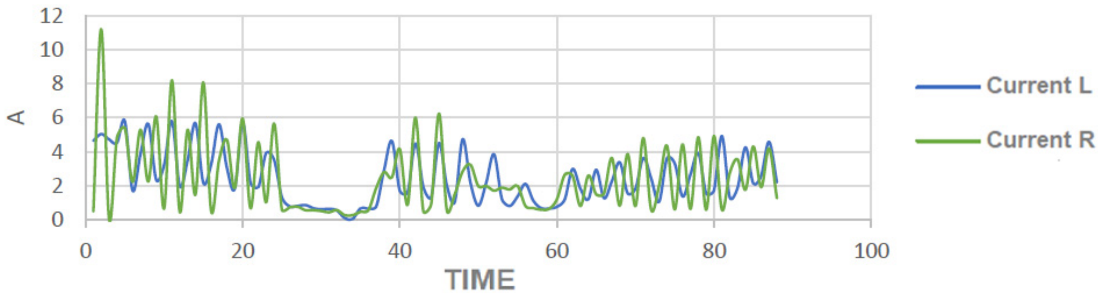

Figure 10. ED control results base exclusively on variation of torque feedback at an average 5 Km/h doing sharp circles.

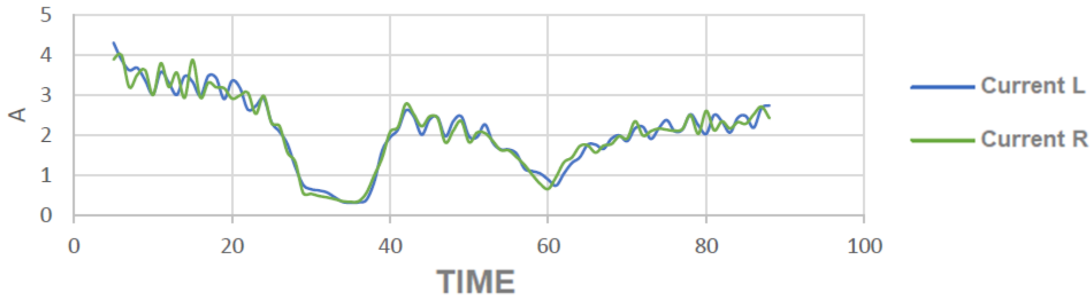

Figure 11. ED control results working adding a steering angle feedback at an average 5 Km/h doing sharp circles.

Considering the use of the vehicle completing a trace of circles, the experimental results obtained with the vehicle driving without a position sensor to measure the steering angle in the driving wheel express that for medium / low speed values (< 15 Km/h) in the LEVs and not sharp turns this approach is good enough and the complexity and difficulties of having additional sensors does not offer any significant advantage over having them included in the system.

However, it is observed that, at higher speeds, the appearance of slips on the wheels causes problem in the ED system to adjust properly the power to be driven on the engines that causes several oscillating inrush peaks of currents (See figure 10). This effect/consequence can be anticipated with this steering sensor and the system, in this case, is able to adjusts the speeds of the wheels before it occurs providing a smoother driving control with less energetic losses (See figure 11).

4. CONCLUSIONS

In the face of the growing environmental revolution of the development of LEVs, where increasingly new products are being developed that advance in the field of clean energy transportation. The installation of ED units in electric vehicles lead to the compliance of one of the basic requirements of this segment of vehicles with more than one drive wheel., to ensure that the two motors of the power train deliver the same torque and can rotate at different speeds, with a significant reduction in weight, guaranteeing lower consumption and a better use of their basic resources.

In this work we discuss the advantages and disadvantages of adding complexity to an ED system by including steering angle sensors or dedicated speed sensors upon a basic differential torque feedback estimated measuring the current injected to the engines as they are proportional

A small weight and low cost hardware system based on two Arduinos CPUs is used to coordinate two standard BLDC motors trough their controllers using the required sensors to measure the three claimed variables of the vehicle has been developed.

A basic evaluation circuit driven at different speeds achieving or not slippage conditions of the drive train wheels. Under non slippery (low/medium speed & non-sharp turning) the increment in complexity offer no significant benefits while this driving consequence appears it can be inferred in advance based in the additional sensing. This effect cannot be easily eliminated but it is possible to minimize it.

From the hardware dimension of the system, adding complex sensing requires an improvement of the immunity to the noise of the circuits and wiring. A clean set of measure signals allows an ease calibration of the proportional, derivative or integral gain of the control algorithm. These values can be selected while driving according to punctual needs of the user: faster response, lower consumption… However noisy signals produced by the EMIF generated in the engines may generated more inefficiencies than advantages.

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