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MECHANICAL DESIGN OF A LOW-COST MODULAR ELECTRIC VEHICLE IN SMALL-SCALE

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Abstract. *The use of electric vehicles is increasing in a complex scenario where it is necessary to reduce the pollutant emissions without increasing the production costs. Around the world, there are many automotive companies and universities developing and creating systems and different concepts for electric vehicles. In the present study, a small-scale prototype of a modular electric vehicle was designed focusing on mechanical development. Distinct from other vehicle/robot prototypes, this small electric vehicle proposed has adjustable features such as wheelbase, track, and center of gravity height. Therefore, it is possible to reproduce different behavior of the vehicle in small scale, of various vehicles, such as sedans and hatches or battery position. This prototype has the concept of modular design, thereby, it has three separated sections: steering chassis, traction chassis, and connect/control unit. This way, it has the aiming to help understand the dynamic behavior and to facilitate the control application. The prototype's traction is made by electric motor connect in each wheel, simulating electric vehicle with four in-wheel motors. As results, a compact, modular and adjustable geometry was designed and constructed. It can be concluded that this paper is an important contribution regarding mobility with different ideas about electric vehicles.*

Keywords: *electric vehicle, modular, small-scale, low-cost.*

1. INTRODUCTION

Concerns about pollution and global warming associated with more restricted environmental regulations and increasing market competition (Holjevac, Cheli, and Gobbi, 2019) have encouraged the study of more sustainable transport alternatives. The electric vehicles (EVs) have been extensively seen as a promising solution to convert sustainable energy into drive energy (Corrêa et al., 2015), instead of the combustion engine (Zhang et al., 2019).

However, the development of EVs still a challenge for the automotive industry (Allègre, Bouscayrol, and Trigui, 2013; Xian, Wang, and Wang, 2014). Unlike conventional vehicles, the EVs do not achieve a standardized configuration. Several studies were developed regarding different assemblies for the EV drivetrain (Eckert et al., 2017), energy storage system (Eckert et al., 2018), and power split using powertrain configuration and control strategy (Kollmeyer et al., 2019; Hu et al., 2019).

Furthermore, working with real EVs is a challenge, once the cost and weight are high and the time spent in the laboratory experiments is long. Aiming to overcome this challenge, small-scale prototypes are an emerging alternative, reducing costs and spent time. Therefore, prototypes and robots, both for research and for didactics, have been constructed and analyzed, such as done by Fajri et al. (2013) and Silva et al. (2008).

Another concept that should be highlighted is modularity, increasingly applied and sought by companies, such as the modular vehicle platform (hybrid and electric configurations) tested by Rambaldi et al. (2011). Modular design can be seen as a production process of units, known as modules, which can be connected to provide a variety of functions (Silva et al., 2014). Huang and Kusiak (1998) show a concept of modular design where components can perform several functions and allows us to arrange the modules in different ways, resulting in product variants. More details about the modular configuration of EVs can be found in Silva et al. (2014).

In this way, this paper aims to develop a concept of low-cost modular electric vehicle in small-scale and presents the characteristics of the developed modular vehicle in 1/5 scale. The details about its characteristics, design, and components dimensions are discussed.

2. STATE OF ART

The modular electric vehicle developed in this project is a modular robot. It can be defined as a system of basic and independent components, identical or not, that connect by manual or automatic to compose systems with different configurations and functions.

Moubarak and Ben-Tzvi (2012) presented a review of the state-of-the-art of modular robots with several examples. One of them was the S-Bots robot. Its modules were autonomous and equipped with nine degrees of freedom. For reconfiguration, the modules presented claws that were attached to the neighboring modules. This type of robot was classified as a reconfigurable modular robot with a configuration change. Other robots that followed this same category were Uni-Rovers, Millibots, and AMOEBA. Another category was presented for different types of locomotion. Usually, the modules are independent and only move when connected. An example shown was the PolyBot, which the modules were assembled in series for different types of locomotion and all modules had their battery, their microcontroller, and their communication system. Other robots in this classification were EM-Cubes, Telecubes, and MTRANm Thor.

Another relevant work was developed by Mutambara and Durrant-Whyte (2000) that presented a modular vehicle robot, which each module presented its hardware and software. Therefore, each module had sensors, motors, communication system, and control system. However, Park and Minor (2004) presented a modular robot and its study of dynamic models and controls. That robot consisted of modules with suspension, traction and steering systems that, when coupled, allowed the movement of the vehicle.

There are innumerable types and methods of control and different types of mobile. Thus, knowledge about the theory of control and the dynamic behavior of robots is necessary to design them properly for a specific application.

3. VEHICULAR DYNAMICS

Different forces act in the vehicle direction of travel, as shown in Fig 1. According to Gillespie (1992), the movement resistance forces on the vehicle are the rolling resistance force (R_x), aerodynamic drag force (D_A), climbing resistance force, vehicle acceleration and hitch force (R_{hx}). With this motion resistance, it is possible to measure the vehicle power demand.

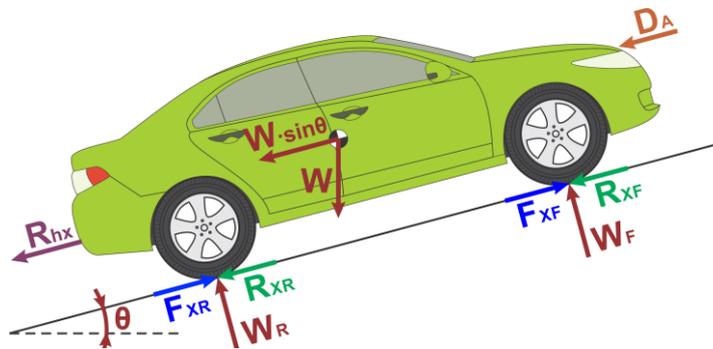


Figure 1. Movement resistance forces on the vehicle.

Therefore, it is possible to predict the performance of a vehicle with the second law of Newton (Gillespie, 1992). The expression for the acceleration is shown in Eq. (1).

$$\frac{W}{g} \cdot a_x = F_x - R_x - D_A - R_{hx} - W \cdot \sin\theta \quad (1)$$

Where W is the weight of the vehicle, g is the gravitational constant, θ is the grade angle, a_x is the acceleration in the longitudinal direction and F_x is the tractive force at the ground.

Another point on the vehicle dynamics is the steering system. At low speeds, the tires do not develop lateral forces and roll without slipping. In this, case the ideal angles for the front wheels are obtained by Eq. (2) and Eq. (3). Where δ_o and δ_i are the steering angles, R_1 is the radius of the turn as experienced by the vehicle centerline, L is the wheelbase and t is the track.

$$\delta_i = \tan^{-1} \left(\frac{L}{R_1 - \frac{t}{2}} \right) \quad (2)$$

$$\delta_o = \tan^{-1} \left(\frac{L}{R_1 + \frac{t}{2}} \right) \quad (3)$$

An important step in the design of a steering system is the determination of the forces and moments on the steering axis. Figure 2 shows an illustration of drive forces and moments on a front-wheel. It is possible to observe the influence of the inclination and position of the steering axis on the steering torque.

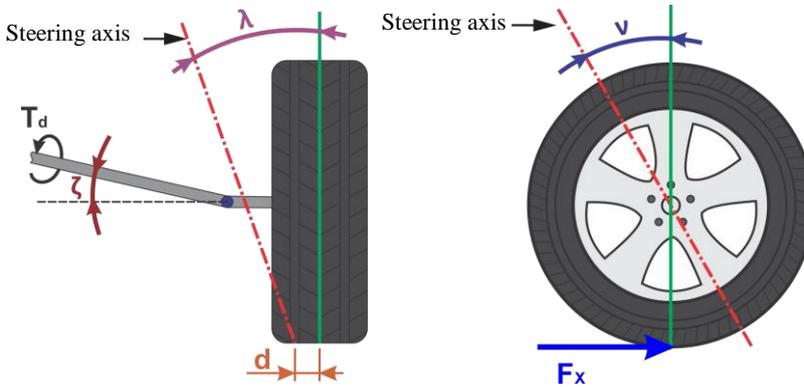


Figure 2. Drive forces and moments acting on a front-wheel.

The tractive force and torque in driveline produce a moment around the steering axis (Gillespie, 1992). Equation 4 defines this moment in the steering axis.

$$M_{SA} = F_x \cdot d \cdot \cos v \cdot \cos \lambda + T_d \cdot \sin(\lambda + \zeta) \quad (4)$$

Where d is the scrub radius, v is the caster angle, λ is the kingpin inclination, T_d is the torque in driveshaft and ζ is the half-shaft angle.

4. METHODOLOGY

For the development of the modular EV in small-scale, the first step was to develop large scientific research of state of the art about techniques in intelligent control of modular robots and electric vehicles. Then, the main project requirements were defined and are presented in the following list:

- Adjustable distance between the wheels, longitudinal and lateral;
- Front steering system;
- Units control for each module;
- Compact geometry easily assembled and disassembled to vehicle modularity.

Based on these requirements, 3D modeling was done. The electrical and mechanical components were dimensioned, allowing defining their pieces and materials. In future works, control strategies will be applied to platform Arduino and tests will be performed on the vehicle. Figure 3 presents a diagram of the design development and execution.

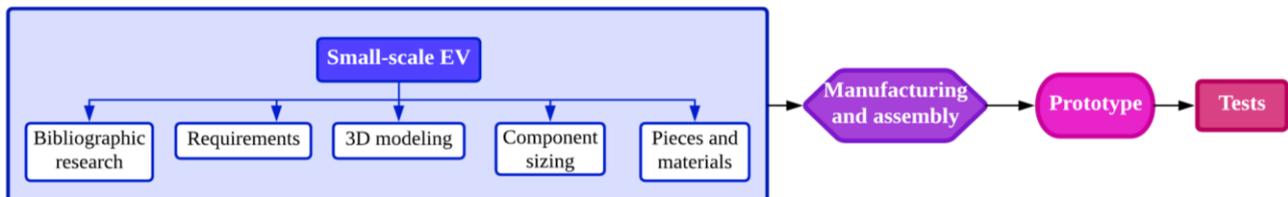


Figure 3. Design development and execution.

5. PLATFORM DESCRIPTION

According to Corrêa et al. (2015), an EV could have different configurations. The first configuration is four electric motors (EMs) coupled directly to the vehicle wheels (in-wheel EM). The second considers the EMs coupled to a differential system that increases the EM speed and the final output torque at the wheels. The third configuration is a combination of the two available propelling systems, where the vehicle rear wheels are propelled by the EM coupled to

the differential system and the front wheels are driven by two in-wheel EMs. However, the EV with an in-wheel drive (the first case) presented the best result considering the Brazilian standard urban driving cycle NBR6601. Also, Eckert et al. (2017) emphasized this configuration shows the maximum performance solution. Therefore, the vehicle in small-scale will have the in-wheel EMs configuration, as can be seen in Fig. 4.

Figure 4 presents the concept of the EV, where the driving desire and the sensors data will be able to define the required power in each wheel, therefore knowing the vehicle dynamics, the control system will be able to distribute the torque needed for each wheel.

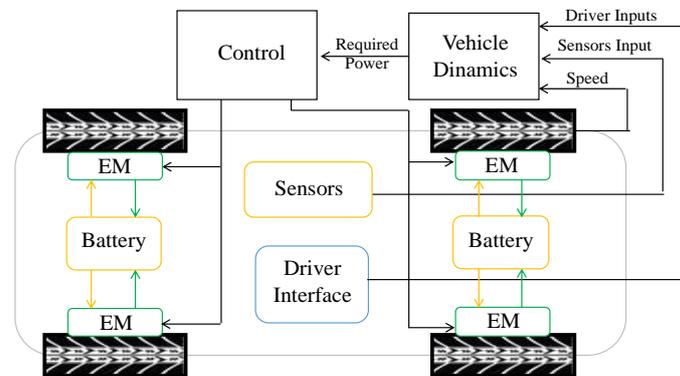


Figure 4. Schematics of the electric vehicle.

The prototype designed at the LabSin (Integrated Systems of the University of Campinas) can be considered as a mid-sized four-wheeled mobile robot. It is a platform for electric vehicle and related algorithms development. To build a system conceptually similar to a real vehicle, the vehicle dynamic concept is used, for example, the Ackermann steering system. In the further text, the modification of a classical automotive chassis is described.

After defining the prototype would be based on, it is necessary to start defining the components. An important component of the vehicle is the tire and, for the correct vehicle modeling, the tire model is required. Therefore, the tire used for this prototype already had its characteristics obtained in Santiciolli (2018). This tire is a pneumatic type, more similar to a conventional vehicle. The tire has size 6"× 2" (diameter × width), the maximum inflation pressure of 50 psi, it is constituted of 4-ply nylon and natural rubber band, and has a load capacity of 90 kg.

The prototype geometric parameters were obtained through the 3D model. Thus, the parameters used to select the EMs are presented in Tab. 1. Vehicle mass, maximum grade angle, maximum acceleration, and maximum speed were estimated. The torque on each wheel and the torque in steering axis were calculated with the information of Tab. 1 by Eq. (1) to Eq. (4).

Four DC-drives were used to propel the EV prototype. The drives used were a pair of motor AK555, which produced the maximum torque around of 2 Nm each when connected to a drive gear system to increase torque. The choice of drives was done based on vehicle dynamic.

Table 1. Electric Motors Parameters.

Engine Torque		Torque in Steer Axis	
Parameter	Value	Parameter	Value
Vehicle Mass (kg)	10.00	Tire Diameter (m)	0.15
Max Grade Angle (°)	20.00	Kingpin Inclination angle (°)	0.00
Max Acceleration (m/s ²)	0.40	Half-shaft angle (°)	0.00
Max Speed (m/s)	1.00	Coefficient of friction	0.80
Rotation Speed in Wheel (rad/s)	13.12	Friction Force (N)	29.69
Force on Each Wheel (N)	8.37	Scrub Radius (m)	0.02
Torque on Each Wheel (Nm)	0.61	Torque in Steer Axis (Nm)	0.59

The prototype was designed using CAD tools. In the design stage, many issues were considered, such as compact size, modularity and manufacturing time. The sizes, thickness, and shape of the components were taken into consideration, once they affect the 3D printer manufacturing process. This modular vehicle is an assembly of three sections — steering chassis, traction chassis, and connect the unit. Figure 5 presents these main modules.

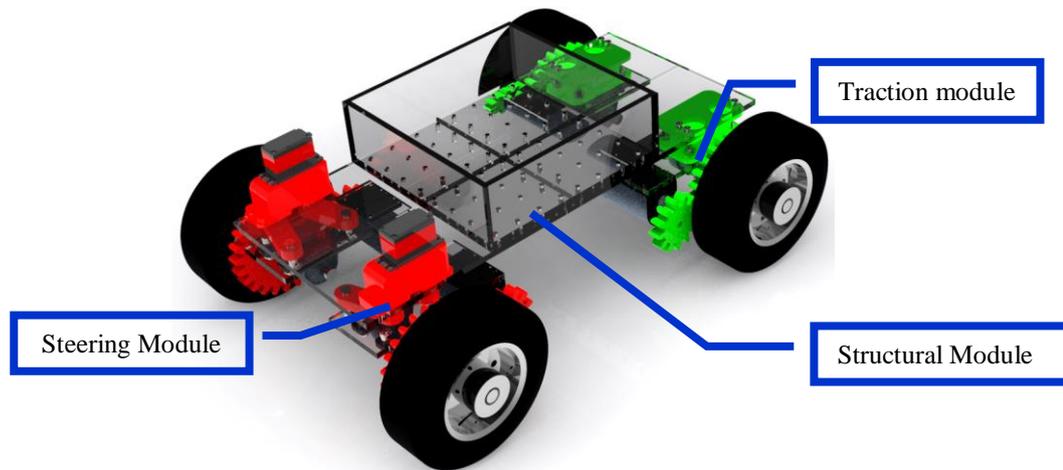


Figure 5. CAD of the electric vehicle.

By assembling these modules in different positions, it allows different vehicle configuration, mainly about the size and number of wheels. As in the prototype case, it is possible to use two traction modules and two steering modules with one control module to make a conventional vehicle. However, by using only one steering module, a tricycle is built. Therefore, depending on the need, a different EV can be designed to meet customer requirements and the modules can be controlled by a central control which communicates with the others.

5.1 Traction system

The locomotion system is based on an independent traction system, which is constituted for one DC motor controlled for the electronic control unit. The structure of the traction system, shown in Fig. 6, is mounted on a rectangular chassis representing a module unit.

This system consists of a DC motor connected to gear that transfers the power to the wheels. To support the drive shaft, bearing housings were added to support the power flow. This gear transmission enables an improvement in the vehicle's torque/speed ratio by increasing the torque transmitted by the engine around two times.

The power comes from the battery and feeds the controllers that set the DC electric motor, fixed to the lower part of the body structure of the vehicle. As mention, a gear on the output shaft of the motor couples to a double-sized one connected to the wheel to allow the vehicle speed to be reduced by half and to double the torque in the wheels. Thereby, it has more power to overcome resistance to motion.

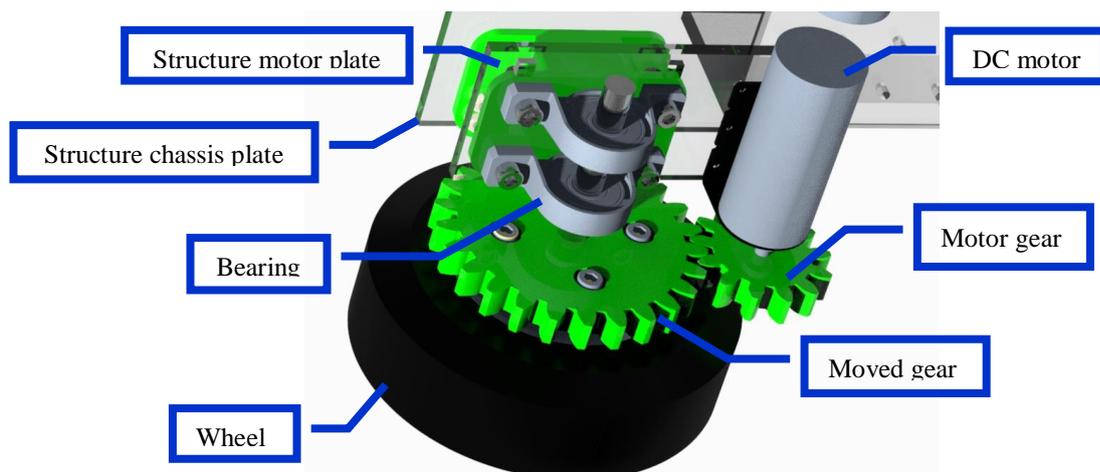


Figure 6. Rear-wheel traction system detail.

This power transmission is the same used in all wheels. The difference between the rear and front is the connection between the bottom and the top structure plates. For the traction module, the connection between these plates is made by a coupling piece which does not allow relative movement between them. In the front case, this connection allows relative movement with the steering system (detailed in subsection 5.2).

5.2 Steering system

During wheel steering, it turns around an axis known as a kingpin. The distance from the kingpin to the center of the tire along the ground plane is called scrub radius, which for passenger vehicles ranges from -18 mm at 20 mm (Reimpell, and Stoll, 1996). This way, the tire rotates practically around its center with a small displacement. Due to the construction of the prototype, it is not possible to position the steering axis close to the center of the tire, therefore, it was necessary to develop a four-bar mechanism for steering the wheel and follow the Ackermann geometry. This is an important point to simulate the vehicle dynamic behavior.

The mechanism will be responsible for steering the wheel as close as possible to its center point, causing the lowest slipping of the tire on the ground. Equations (5) to (11) present the synthesis of the four-bar mechanism (Norton, 2010).

$$K_1 = \frac{C_1}{C_2} \quad (5)$$

$$K_2 = \frac{C_1}{C_4} \quad (6)$$

$$K_3 = \frac{C_1^2 + C_2^2 - C_3^2 + C_4^2}{2 \cdot C_2 \cdot C_4} \quad (7)$$

$$K_4 = \frac{C_1}{C_3} \quad (8)$$

$$K_5 = \frac{C_4^2 - C_1^2 - C_2^2 - C_3^2}{2 \cdot C_2 \cdot C_3} \quad (9)$$

$$\theta_3 = 2 \cdot \tan^{-1} \left(\frac{\sin \theta_2 \pm \sqrt{K_1^2 - 2 \cdot K_1 \cdot \cos \theta_2 - K_4^2 \cdot \cos^2 \theta_2 - K_5^2 + 2 \cdot K_4 \cdot K_5 \cdot \cos \theta_2 + 1}}{-K_1 + (1 + K_4) \cdot \cos \theta_2 + K_5} \right) \quad (10)$$

$$\theta_4 = 2 \cdot \tan^{-1} \left(\frac{\sin \theta_2 \pm \sqrt{K_1^2 - 2 \cdot K_1 \cdot \cos \theta_2 - K_2^2 \cdot \cos^2 \theta_2 - K_3^2 + 2 \cdot K_2 \cdot K_3 \cdot \cos \theta_2 + 1}}{(-K_1 + (1 - K_2) \cdot \cos \theta_2 + K_3)} \right) \quad (11)$$

Where C_1 is the length of bar one, C_2 is the length of bar two, C_3 is the length of bar three, C_4 is the length of bar four, θ_2 is the angle provided by the servomotor, θ_3 is the rotation angle of bar three and θ_4 is the rotation angle of bar four.

The four-bar mechanism was developed by an optimization based on the genetic algorithm method. The angles required the vehicle to steer, the prototype geometrical dimensions and servomotor capacity were defined as constraints on optimization. The optimization algorithm tests values for the bar lengths of the mechanism and its position on the structure chassis plate and compares the wheel center variation during wheel steering, looking for the setting that generates the smallest variation.

For the vehicle be able to make a turn with a radius of 1 m, by Eq. (2) and Eq. (3), the inner and outer wheel must steer 15 and 30 degrees, respectively. The steering angles were calculated for the most critical case, where the wheelbase and track assume their highest values. The selected servomotor can rotate 180 degrees, so the four-bar mechanism must reach the steering angles with the servo motor rotation.

Figure 7 presents the wheel center displacement for the optimization setting. Optimizing according to the design constraints, it was able to find a configuration that the wheel displacement has approximately 5 mm in the longitudinal direction and 10 mm in the lateral direction. This variation occurs for the most critical case of vehicle steering.

From the dimensions obtained in the optimization, the mechanism was built by 3D prototyping. Figure 8 shows the designed steering system.

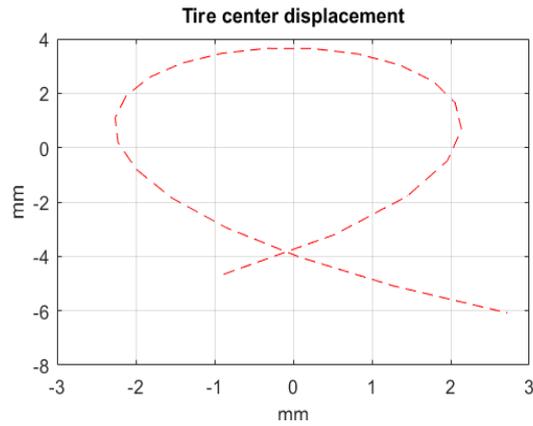


Figure 7. Optimization result.

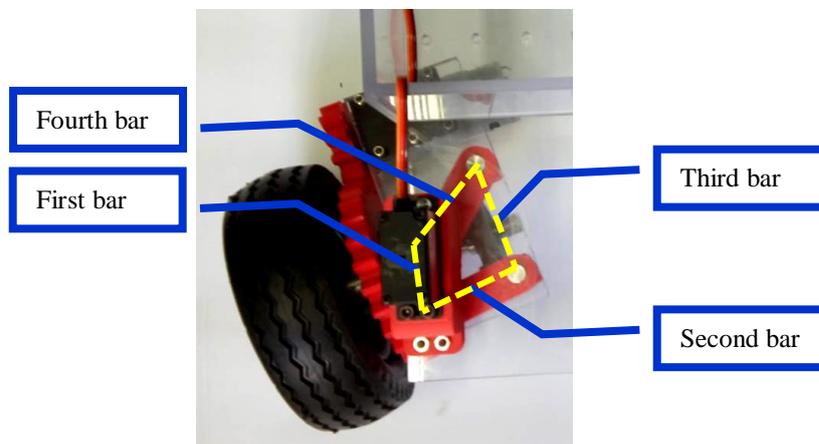


Figure 8. Front steering system detail.

5.3 Size adjustment system

The prototype vehicle presented in this paper is a modular structure robot. As illustrated in Fig. 9, it consists of a chassis for accommodating the steering mechanism, transmission system and control system, as the modular vehicle three separated sections — steering chassis, traction chassis, and connect/control unit.

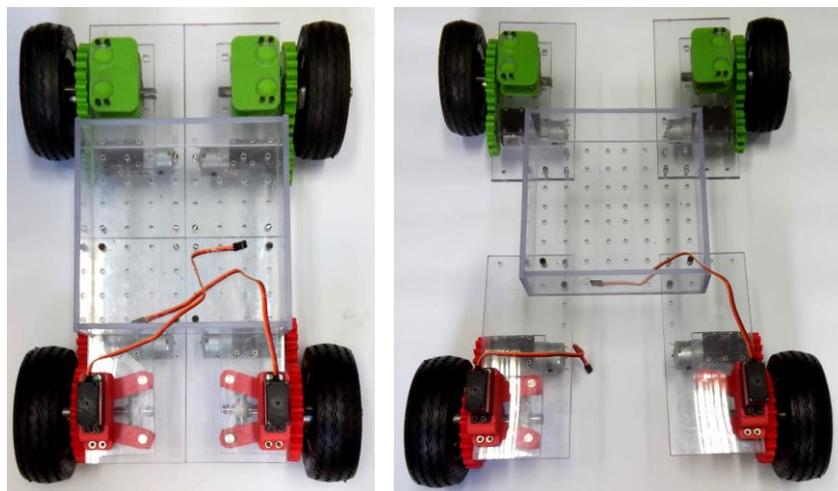


Figure 9. The prototype complete close and open.

Modularity at the mechanical and control structure is the key to solve design issues and are considered concurrently during the design process resulting in a sophisticated mobile robotic platform where it can be adequate according to the desire. Typical, the construction of the mobile robot has a chassis with a constant size dimension, therefore, this is another different point of this prototype. On it can modify physical characteristics such as wheelbase, front track, rear track, position and height gravity center. Also, in this prototype, the powertrain system can be changed: front-wheel drive (FWD), rear-wheel drive (RWD), or all-wheel drive (AWD). These prototype adjustments allow reproducing the behavior, in small scale, of various vehicles, such as sedans and hatches.

6. RESULTS

Figure 10 presents the final mechanical design of the electric vehicle prototype details and other important points like sensors and electric equipment. The modular mobile platform will have only one superordinate master control system and several slave control blocks. The serial communication will be applied and each module will be assembled from independent autonomous control blocks. For control of the traction system, the DC motors (Fig. 4) associated with an encoder will be used. Therefore, optical encoders connect in each wheel shaft, will provide velocity information to the microcontroller. A four-channel high power H-bridge drive board will be interfaced to a microcontroller board. The overall hardware architecture system is present in Fig.10.

Also, for inertial navigation, gyroscopes and accelerometers will be used to measure the rate of rotation and acceleration, respectively. For that, a low-cost sensor will be selected, once the sampling rate depends on the dynamic of the robot. In case of a high-speed robot, it is necessary a higher bandwidth, which requires a faster sampling rate and is not the case in this application.

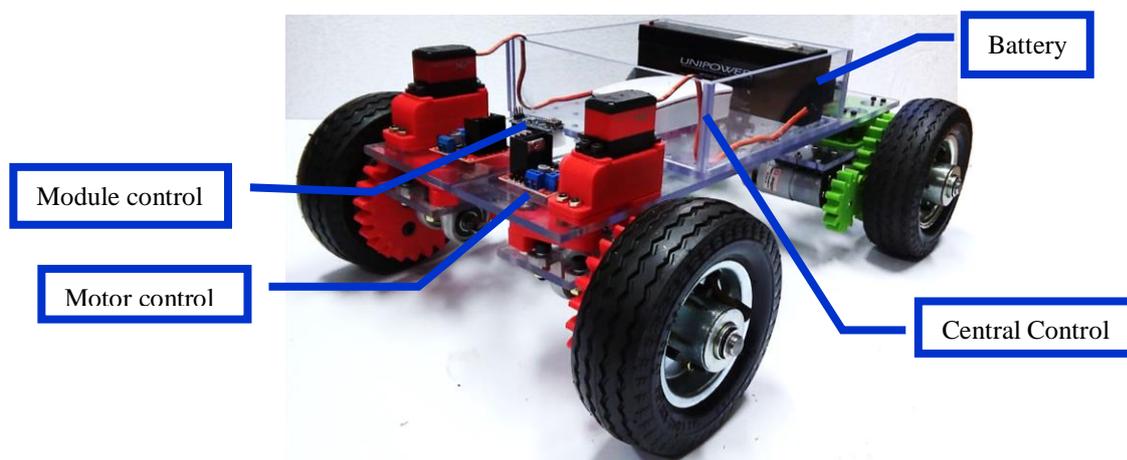


Figure 10. The overall hardware architecture system.

An important point of this configuration is that the ratio of the rear wheel angular speeds depends only on the steering angle and not on the unstable adhesion of individual wheels, therefore, the Ackermann steering is supported by the rear wheel speeds ratio.

One disadvantage of the presented independent drive units architecture is that the chassis becomes less controllable in case of misbehavior of one of the drive units. This can happen if there are communication problems.

7. CONCLUSION

Given the relevance of the electric vehicle as an alternative mean of transportation, it is clear the need to expand knowledge about this subject. Therefore, this paper presents an overview of the primary design state of a modular electric vehicle. In this way, the methodology presented was applied and the results are the prototype design and construction, its main characteristics, and the components specifications. Unlike most common prototypes, the modular one developed in this paper could have adjustments as changing wheelbase, track and height of the gravity center for simulated different behaviors. Finally, it can be concluded that the objective proposed by this work was achieved and the development of a low-cost modular electric vehicle in small-scale was shown and presented an interesting result maintaining the same dynamic behavior of standard vehicle with the Ackermann geometry. Moreover, building a modular vehicle provides a stringent test bed for new concepts and approaches in mechanical design, chassis and also the design for electronic hardware and software.

However, future studies should develop a control system considering the necessity of fast response, less interference caused by external noise and more reliability due to the application. With this new EV system, the module can be adequate according to the user desirer and other devices can plug-in. Therefore, it will be possible to test the behavior of

an EV with different conditions including the positioning of the batteries. Consequently, this paper is an important contribution regarding mobility with different ideas about EVs. Also, the combination of the mechanical design of the chassis, the motion control, and multiple sensors allow the exploration of control theory for practical application. Thus, it provided a convenient platform for control and test using a fuzzy logic algorithm for motion control and power-split management.

8. ACKNOWLEDGEMENTS

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