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Design, Analysis, and Mechanical Assembly of a Three-Wheeled Solar-Powered Electric Vehicle

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Abstract: The limitation of conventional energy source and the dependency on them for energy generation imposes the need to diversify energy sources and taking steps towards saving them. In Kuwait, energy generation is based on fossil fuel which is limited and will one day vanish. Therefore, there is a strong need to start using electric vehicles instead of petrol-powered vehicles. Accordingly, the design, implementation, and performance evaluation of a solar-powered electric vehicle is proposed. The proposed vehicle is powered by the energy generated by photovoltaic (PV) modules and stored in a battery. The vehicle is equipped with a monitoring system to check the voltage and current levels of the PV modules. Several tests to evaluate the performance of the vehicle were carried out and the results prove the ability of the vehicle to be driven for a long duration.

Keywords: Renewable Energy; Environment; Solar Energy; Solar Vehicle; Electric Vehicle; Photovoltaic Module; Motors; Monitoring System; Mechanical; Sensor; Microcontroller; Solar Controller.

1. Introduction

Renewable energy sources are not pollution-free, yet there is a noticeable focus nowadays on them as they are friendly to the environment. Renewable energy sources are various and include wind, solar, hydro, and geothermal energies. By 2018, according to the renewable energy policy network, nearly all countries plan to invest in renewable energies and have adopted some form of renewable energy target [1].

The increase in serious diseases and different forms of cancer as well as the greenhouse effect have been linked to the exhaust emissions from automotive vehicles [2][3]. In 2012, 3.7 million death tragedies and 18% premature births due to air pollution have been reported by the World Health Organization (WHO) [4-6].

Solar energy attracted more attention compared to other renewable energy sources as it is available, free, clean, and does not have direct environmental risks. Solar radiations can be converted into direct electricity by using photovoltaic (PV) cells. A PV cell is an advanced technology that is based on semi-conductor material. Multiple PV cells are combined in series and parallel to form a photovoltaic (PV) module in order to get higher amount of electrical power. The electrical power extracted for the PV modules can be stored in batteries to be used for different purposes such as powering the motors of an electric vehicle.

A survey was carried out among 200 individuals in Hong Kong to examine people's attitudes towards electric cars. The results of the survey show that people recognize the positive environmental benefits of electric cars but prefer not to buy one due to the high cost. The technical limitations of electric cars such as the short driving distance are not considered a major problem [7]. The utilization of public procurement as an instrument to enhance a market for electric vehicles was investigated in [8]. The proposed strategy was to create a buying power and develop a second-hand market for electric vehicles.

The importance of considering electric buses as an eco-friendly alternative to the conventional buses was proposed in [9]. A total cost of ownership (TCO) model was established by considering direct cost and indirect cost. The study showed that electric buses would be economical, giving 30-40% advantage on fuel and maintenance and could prove to be a positive multiplier for socio-economic and environmental gain.

A continuous increase in sales of electric/hybrid vehicles has been registered. The registration of electrically chargeable vehicles in the European Union

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(EU) increased in 2018 by 33% compared to the previous year with 48% grow in sales [10].

In the following sections, the motivation behind building the solar vehicle and the problem that is being addressed are explained. Similar projects are also reviewed.

1.1. Motivation and Problem Statement

The dynamic, expensive, and busy lifestyle in Kuwait imposes the need to start using solar-powered vehicles instead of petrol-powered vehicles. In Kuwait, people refill their vehicles with petrol around two to three times a week. The potential rise in petrol prices causes financial problems for limited salary employees. Accordingly, using solar vehicles would significantly be useful for people in Kuwait due to their expensive and busy daily schedule.

Environmentally speaking, fossil fuel is a limited natural resource and one day it will be depleted. The word's oil resources have predicted that it will be depleted by 2038 according to the current trends of oil consumption [11]. In Kuwait, there is a dependency on fossil fuel for energy generation for heating, electricity, transportation, and manufacturing. All of these operations results in a high percentage of air pollution due to the burning of fossil fuel. The humid and hot weather of Kuwait plays a role in making the air easily polluted by the carbon dioxide resulted from burning the fuel. Therefore, by using solar vehicles the percentage of air pollution would be reduced and fossil fuel would be saved for next generations due to the diversification of energy sources.

The solar energy received by earth in one hour can fulfill all energy needs for one year [12]. The US government has adopted a national goal of deploying one million electric vehicles (EVs) by 2015. In Canada, Ontario, the Ministry of Transportation, through its Green Investment Fund, is spending $20 million to build 500 electric vehicle charging stations (EVCSs) [13]. Around one million EVs with a demand of about 70,000 on-street charging spots is envisioned by the German National Electric Mobility Platform (NPE) by 2020 [14]. Several countries around the world have collaborated to form the Electric Vehicles Initiative (EVI) which is dedicated to expedite the growth of EVs worldwide [15].

EV charging stations can be divided into four main categories [16,17]:

1- Residential Charging Stations: Basically, a home charging station where the user plugs in the EV to charge overnight.

2- Charging While Park: Can include parking at malls and parking stations where EV recharges while user takes advantage of nearby facilities.

3- Charging at Public Charging Stations: Used for charging while parked for longer periods to allow for longer distance trips.

4- Battery Swaps: Intends to match the refueling expectations of regular drives achieved with EV battery swap.

1.2. Literature Review

The MIT Solar Electric Vehicle Team (SEVT) is a team of students who want to use alternative energy transportation based on renewable energy [18]. Their goal is to have a better future for the next generation by investing in renewable energy. The electrical system in the proposed solar vehicle is a high voltage system that includes array, battery pack, and motors. The low voltage system which is controlled by the driver contains a steering wheel, throttle, camera, and horn. The aerodynamic body for the proposed flux vehicle is designed to be an asymmetric shape which allows the vehicle to sail in cross-winds and helps in further reducing the drag. The flux's chassis is designed to be suitable to save weight and allow better integration between chassis and body. For the battery pack, they used lithium ion cells, which have microprocessors to monitor the temperature and voltage of the pack in real time, and alert the driver if any problem arises [18].

The University of Malaya built an economic solar vehicle to participate in the World Solar Challenge (WSC) using off-the-shelf components which are easy to purchase [19]. They participated in the 2007 WSC with their vehicle "Merdeka" which was made from photovoltaic panels for rooftops, batteries for stand-alone PV, and electric motors. After that, the team decided to participate again at the 2009 challenge by reusing the same electrical and mechanical parts but the chassis was changed and the main body was made of aluminum. For the electric part, they used two 180 W mono-crystalline silicon PV panels. For the solar MPPT charge controller, they used OutBack MX60 because of its good safety factor. Two units of brushless DC motors with an operating voltage of 48 V and maximum current of 35 Amps were used to move the 180 kg vehicle.

The Power of One is one of the most famous teams who built a solar vehicle that can defeat any challenge. In spring 1999, they built a vehicle that can travel for long distances and bear different weather conditions. Furthermore, the vehicle was awarded the following: world distance record for a solar powered vehicle, first solar vehicle that operates below freezing temperatures, and world distance record for a vehicle pulled by hand (Xof1, 2009). The specifications of the vehicle are so simple that encourage anyone to implement it. The proposed solar vehicle weighs 300 kg with 3-wheels configurations, 2 in the front and 1 in the rear. It is made of aluminum and is covered by fiberglass and reinforced by carbon fiber. The battery pack used is 96 V with 893 mono-crystalline solar cells covering the vehicle with an efficiency of 15%. The motor that was used is a brushless DC with 84-108 V [20].

The UJ Solar Vehicle project was designed and implemented to participate in the 2012 South African Solar Challenge [21]. In this project, the main parameters used in the selection and design of the components for the solar vehicle are electrical efficiency, mass, and power consumption. They used two 165 V Marand motors to control four wheels which had a combined efficiency of up to 98%. The implemented vehicle was able to drive 110 km/h on a test track.

A prototype of a solar vehicle was done by four students from BRAC University, Dhaka, Bangladesh [22]. Students were motivated to focus on the solar vehicle project because they believe that the vehicle is the main transportation vehicle in Dhaka. The project is designed and structured to have a vehicle that can run for 35 km. They designed the vehicle to be lightweight to reduce the energy needed to move it. They calculated the rolling resistance force which is the force that is resisting the rolling motion of the tires on the road. The team also calculated the aerodynamic drag and force of acceleration. The minimum wattage of the used panels is 201 W. The body of the vehicle was made from mild steel. The vehicle has 4 wheels and can carry 2 passengers. The team had designed and built a suspension system, a steering system, and a braking system. The implemented vehicle can move with a speed of 60 km/h with a total power of 4 kW.

2. Design and Analysis

In this section, the different systems needed for the design of the solar vehicle are explained. A detailed analysis of the chosen hardware components is done followed by an explanation of the mechanical design aspects of the vehicle.

2.1. Electrical System

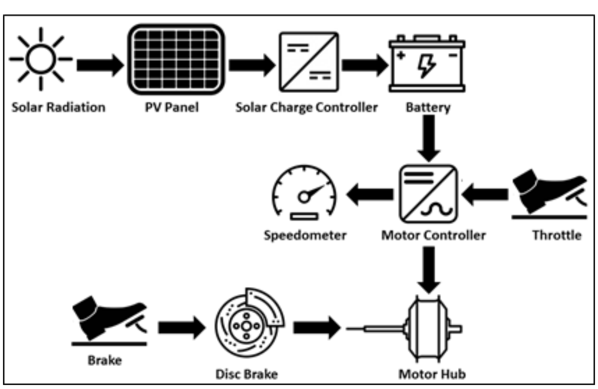

Figure 1. Electrical system architecture

The electrical system architecture of the solar vehicle is shown in Figure 1. This architecture demonstrates all the components used to build the solar vehicle and the relationship between the components. First, the photovoltaic modules convert the sun radiation to electricity. The generated electricity is transferred from the photovoltaic modules to the battery by the solar charge controller. The power is then supplied from the battery to the motor controller where the foot throttle and speedometer are connected. By using the disc brake, the motor can be stopped. In the following subsections, an analysis of the chosen components of the electrical system is presented.

2.1.1. Motors

In order to choose the motors for the vehicle, the motor power rating must be calculated. The motor power rating calculation involves three forces: the rolling resistance force, the drag force, and the acceleration force. The rolling resistance force is the force resisting the rolling of the tire as they roll on a surface. It can be calculated as follows:

$$F_{Rolling} = \mu_r * W = 0.01 * 500 * 9.8 = 49\, N \quad (1)$$

Where,
μ_r: The coefficient of rolling resistance which is equal to 0.01 for an ordinary vehicle tires on concrete.
W: The weight of the vehicle which is equal to 500 kg.

Aerodynamic drag force is the force of the air that prevents the vehicle from moving through it. It can be calculated as follows:

$$F_{Drag} = 0.5 * C_D * A * \rho * v^2 = 0.5 * 0.1 * 1 * 1.2 * (27.78)^2 = 46.3\text{ N} \quad (2)$$

Where,
C_D: The coefficient of drag of the vehicle that must be chosen according to the shape of the vehicle which is equal to 0.1
A: The frontal area which is equal to 1 m^2
ρ: The air mass density which is equal to 1.2 kg/m^3
v: The velocity of the vehicle relative to the air which is equal to 27.78 m/s

The acceleration force is Newton's second law of motion. It can be calculated as follows:

$$F_{Acceleration} = m * a = 500 * 0.3086 = 154.3\text{ N} \quad (3)$$

Where,
m: The mass which is equal to 500 kg
a: The acceleration which is equal to 0.3086 m/s^2 as a result of dividing the velocity (27.78 m/s) by the approximated time (90 s) to reach the maximum speed.
The sum of the three forces is equal to 249.6 N which is used to get the motor power rating (P_{Motor}) as follows:

$$P_{Motor} = (F_{Rolling} + F_{Drag} + F_{Acceleration}) * v = 249.6 * 27.78 = 6{,}933.8 \text{ W} \quad (4)$$

Hence, according to the calculated motor power rating the QS Motor 8000W V3 was chosen. The chosen motor is a brushless DC permanent magnet outer rotor in-wheel hub motor for electric vehicles with $8000\ W$ rated output power.

2.1.2. Motor Controller

The motor controller connects all the components with each other in order to control the vehicle switch, throttle, brake, and speedometer. When the motor controller receives a signal from the throttle, it sends the instruction to move the motor. If the controller receives a signal from the brake, it sends the instruction to move the disc brake to stop the motor. APT programmable sine wave Motor controller was selected as it is suitable for the chosen QS Motor $8000\ W$. APT programmable sine wave controller is specially designed for electric vehicles or electric scooters. The operating range of the controller is between $42\ V\ to\ 120\ V$. The peak phase current is $600\ A$.

2.1.3. Speedometer

Electric vehicle speedometer is a device that indicates the speed of a vehicle. The chosen speedometer is from QS Motor Company and it is a programmable speedometer which can be easily designed for the vehicle. It has a rated voltage between $48\ V - 144\ V$ and can show time, driving distance, speed, and voltage.

2.1.4. Throttle

Foot pedal is used in vehicles by the driver to control the vehicle's operation. The chosen throttle is 0-5 V Electric Vehicle Throttle Pedal from QS Motor Company. It has different input and output voltage ranges which are compatible with the chosen motor and controller.

2.1.5. Disc Brake

A disc brake consists of brake pads, a caliper, and a rotor. The brake pads squeeze the rotor and the friction between the pads and the disc slows down the disc. The chosen disc brake is a foot disc brake assembly with mechanical parking brake from QS Motor Company. It has a left caliper and a right caliper with T-shape hose connector.

2.1.6. Battery

A Lithium-ion battery $96\ V\ \ 60\ Ah$ was chosen to power the motors since they need $96\ V$ to operate and a very high discharge current. The chosen battery charges in a fast manner as the only source of energy for the vehicle are the photovoltaic modules.

2.1.7. Photovoltaic Modules

The chosen battery needs $1152\ W$ to be charged according to its energy which can be calculated as follows:

$$E = 96\ V * 60\ Ah = 5760Wh \quad (5)$$

The sun in Kuwait is available at least five hours per day. Thus, the needed power can be found:

$$Power = \frac{5760}{5} = 1152 \text{ W} \quad (6)$$

Monocrystalline Solar modules DSP-300W were selected as they can give $300\ W$. Hence, the total number of the needed modules is:

$$Number\ of\ PV\ Modules = \frac{1152\ W}{300\ W} = 3.84 \approx 4\ Modules \quad (7)$$

Thus, four modules connected in series were used.

2.1.8. Solar Charge Controller

A solar charge controller for off-grid systems was used to control the charging and discharging process of the battery. The chosen controller has $96\ V$ rated voltage and $50\ A$ rated charge and discharge current.

2.2. PV Monitoring System

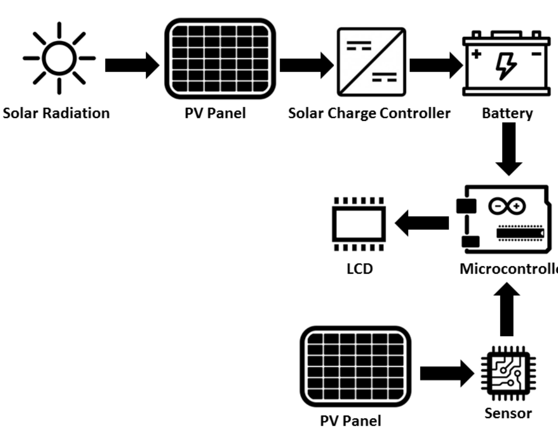

Figure 2. The system architecture of the monitoring system

The PV modules are the main component of the solar vehicle and any malfunction in one of them will stop charging the vehicle's battery. A PV monitoring system is essential to monitor the current and voltage levels of each PV module and to recognize which PV module in particular is experiencing a high drop in its current or voltage levels. Figure 2 shows architecture of the monitoring system. A small PV module is used to charge a $12\ V$ battery. The power transfer from the PV module to the battery is done through the solar controller. The charged battery is used to power Arduino microcontroller which is connected to four sensors and a LCD. The sensors read the voltage and current levels of the vehicle's PV modules and send the readings to Arduino. Arduino then sends the data to be displayed on the LCD. A detailed analysis of each component used for the PV monitoring system is presented in the following subsections.

2.2.1. Arduino Mega

Arduino Mega microcontroller board which is based on the ATmega2560 was chosen as it has 54 digital I/O pins and 16 analog inputs which are enough number of pins for the PV monitoring system.

2.2.2. Voltage and Current Sensor Board

AttoPilot Voltage and Current Sense Breakout $45A$ is a small voltage and current sensor printed circuit board. It was chosen as it can sense a maximum voltage of $51.8\ V$ and a maximum current of $44.7A$.

2.2.3. LCD

A basic 16 character by 2 line LCD with a green background and black characters was used. The used LCD needs 11 general I/O pins to be interfaced.

2.2.4. Photovoltaic Modules and Battery

The energy of the $12\ V$ battery of the monitoring system with the capacity of $1.2\ Ah$ feeding the Arduino microcontroller can be calculated as follows:

$$E = 12V * 1.2Ah = 14.4\ Wh \tag{8}$$

Therefore, the needed power can be calculated as follows:

$$Power = \frac{14.4}{5} = 2.88\ \text{W} \tag{9}$$

The selected photovoltaic module to charge this battery is a $0.75W$ module. Accordingly, the total number of modules is:

$$Number\ of\ PV\ Modules\ = \frac{2.88W}{0.75W} = 3.84 \approx 4\ Modules \tag{10}$$

Therefore, four modules connected in series were used.

2.3. Mechanical Design

The mechanical design of the solar vehicle is all about aerodynamics and how to make it strong enough to handle heavy weight and to be lightweight at the same time. The design was made in SolidWorks software. The material that was used is Aluminum (A6061) and the diameter of the pipe is $38.1\ mm$. The design of the chassis is shown in Figure 3. The body of the vehicle is designed to have a small aerodynamic ratio. The design of the outer body of the vehicle is shown in Figure 4 and the inclusion of the chassis inside the body is shown in Figure 5. A stress analysis was conducted for the designed chassis and body. According to the analysis, the vehicle can handle up to $300\ kg$ and the weight of the chassis is $198\ kg$.

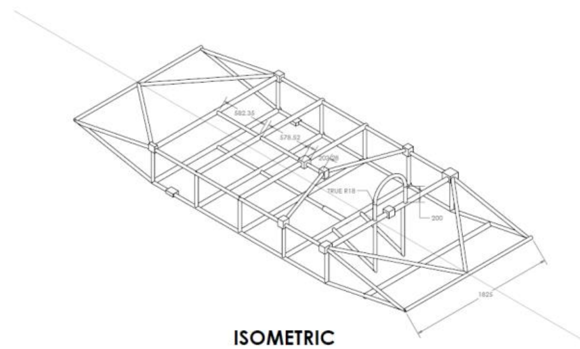

Figure 3. The designed chassis of the solar vehicle

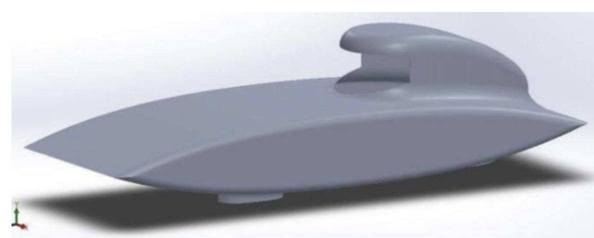

Figure 4. The designed outer body of the solar vehicle

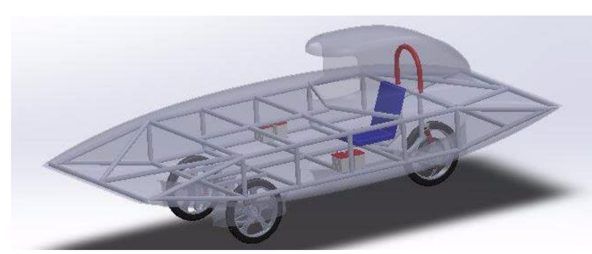

Figure 5. The chassis inside the body

3. IMPLEMENTATION

This section demonstrates the mechanical implementation of the solar-powered electric vehicle. The PV monitoring system connection is also explained.

3.1. Mechanical Assembly

Implementing the chassis is the first step of the mechanical implementation of the solar vehicle. Aluminum pipes were cut into small pieces and welded according to the design of the chassis. Figure 6 shows the implemented chassis. After building the chassis, the steering and suspension systems were installed. Then, the rear wheel was installed, and the disc brake was added to the motor. From the disc brake to the driver seat, brake pedal and the throttle pedal were connected. Next, four PV modules were fixed on the vehicle. Finally, all the sides and bottom of the vehicle were covered by Aluminum.

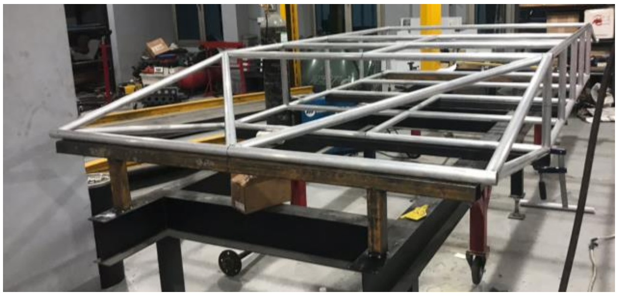

Figure 6. Chassis welding

3.2. PV Monitoring System Implementation

In order to implement the PV monitoring system, Arduino code was written to read the values of the voltage and current sensors which are connected to the batteries. The voltage and current values are displayed on the LCD and a push button was used to switch between them. The connection between the system's components was done on a breadboard.

4. EVALUATION

In this section an evaluation of the overall performance of the implemented solar-powered electric vehicle is presented. A test to evaluate the functionality of the PV monitoring system is also explained followed by design challenges. Lastly, the vehicle's cost is evaluated.

4.1. Evaluation of the Vehicle Performance

Figure 7. The implemented solar-powered electric vehicle

The evaluation of the performance of the solar-powered electric vehicle was done by first testing the speed of the motors. The software of the motor controller can show real time information such as the speed of the motor in RPM, throttle voltage, and direction of the motor. By pushing the throttle pedal, a signal to run the motors is sent by the motor controller. The highest speed achieved by the motors was 1307 RPM.

The second test of the vehicle was the driving test. The vehicle was driven on a sunny day for 39 $minutes$ starting with a fully charged battery by the PV modules. After driving the vehicle for 39 $minutes$, the battery was still almost full as it was being charged during the ride by the PV modules. Figure 7 shows the final prototype of the proposed solar-powered electric vehicle during the test.

4.2. Evaluation of the PV Monitoring System

The functionality of the PV monitoring system was tested by covering one PV module to demonstrate a shadowing scenario during a sunny day. As shown in Figure 8, the three uncovered PV modules have voltage levels while the voltage level is zero for the covered PV module.

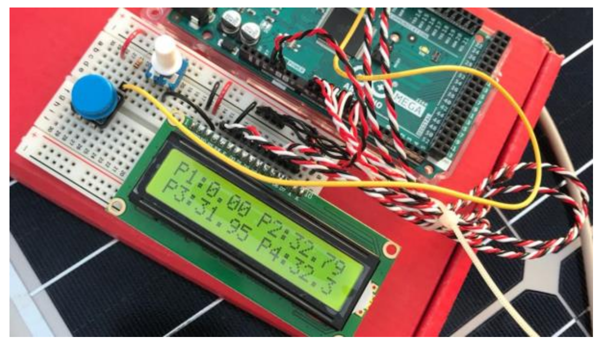

Figure 8. Voltage levels of the four PV modules

4.3. Design Challenges and Limitations:

It is roughly estimated that the proposed solar-powered car has a driving range of approximately 30 km or 1 hour of battery life, assuming operation with a fully-charged battery when it is not a sunny day.

The design and implementation of the proposed solar powered car was a challenging task. This is mainly due to the fact that none of the authors had background experience in mechanical engineering. It was a difficult task to execute a project of this large scale. Furthermore, designing the mechanical assembly using SolidWorks software was demanding as well.

4.4. Cost Evaluation

A brief description of the components used, their associated costs, and the number of units needed for implementing the solar-powered electric vehicle is provided in TABLE I. The total cost of implementing the car is considered within the normal range of an average car price.

TABLE I. DETAILED COST OF THE VEHICLE

Item	Quantity	Cost ($)	Total ($)
6m of Aluminum 6061 Pipes	9	33.5	301.5
QS Motor 8000W	2	650	1,300
Motor Driver Controller	2	394	788
Bluetooth	1	30	30

Adaptor for the Controller			
Throttle Pedal	1	48	48
Speedometer	1	68	68
Disc Brake	1	88	88
Li-Ion Battery 96V 30Ah	2	1,006.82	2,013.64
300W Solar Module	4	117.49	469.96
Solar Charge Controller 96V 50A	1	254.8	254.8
Arduino Mega	1	58	58
Voltage and Current Sense 45A	4	19.95	79.80
16x2 Character LCD	1	13.95	13.95
Steering and Suspension Systems	1	410	410
Rim	1	83	83
Driver Seat	1	597	597
Battery 12V 1.2Ah	1	12.46	12.46
Solar Charge Controller 12V	1	28.24	28.24
0.75W Solar Module	4	5.82	23.28
Aluminum Sheets for the Body	1	232.71	232.71
MC4 Connecter	4	6	24
Aluminum Welding	1	4,976.78	4,976.78
Front and Rear Lights	2	8.63	17.26
Total Shipments	1	497.68	497.68
Total ($)			**12,416.06**

5. CONCLUSION

In this paper, the electrical and mechanical aspects for the design of a solar-powered electric vehicle were explained including the decisions taken for the components' choices. The different vehicle's systems were implanted and evaluated through several tests. The designed solar-powered electric vehicle is equipped with a PV monitoring system so that the driver can check the voltage and current levels of the PV modules. The implemented vehicle can accommodate one passenger and handles up to 300 kg. It is roughly estimated that the proposed solar-powered car has a driving range of approximately 30 km or 1 hour of battery life, assuming operation with a fully-charged battery when it is a cloudy day.

Future work includes but is not limited to adding a backup battery in case of emergencies and an electrical plug to charge the battery at night or in the case of a cloudy weather. Showing the remaining driving distance according to the battery charge is an extra feature to be added to the touch screen.

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