Design and Testing of Solar/Electric Cart

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Abstract. In the current study we report design and testing of a light-weight electric/solar four-wheel drive cart capable of running at speeds in the order of 30 mile/hour. The cart can carry 4 passengers and transport attached additional load of about 500 kg. The battery block consists of LiFePO₄ cells and provides 6000 Watt power to 4 hub motor wheels, each of which are rated 1500 Watt. The 600 Watt solar array secured on the roof provides steady recharging for the lithium-ion batteries. The power distribution and control of hub motors is executed by special programmed microchip controllers and is very important for safe operation of this four-wheel drive vehicle. The commercial MPPT charge controller is installed to operate the amount of power for battery recharging. During operation the battery recharge could be executed using power of solar panels. Willingness to minimize dependence on the grid which operates 120V 15A, has led us optimize the required tractive effort while minimizing the weight of the cart. The cost of experimental electric/solar four-wheel drive cart is presented by table 1. Many elements of discussed prototype are taken from the shelf, i.e. purchased at the market price. So, the commercial cost of such prototype in mass production is expected to be significantly cheaper.

Keywords: Solar/electric cart, electronic differential speed control, Lithium-ion battery

1. Introduction

With the invention of electricity, build-up of electric grids in most of the developed countries across the world, people attempted to increase the amount of energy generated by natural sources such as sun and wind. These efforts intensified in the last decade by production of solar electricity. Last year 2% of electricity produced in the world, was generated by solar cells [1]. For years we have witnessed the design and use of electric cars as well as their smaller derivatives, i.e. electric carts, electric trikes and bikes [1-4]. The first solar/electric racing cars built by automotive companies did compete in the US, Australia, and other countries. However, their big size did not allow them to run along conventional city streets or even highways. In 2009-2014 Advanced Electronic Technology Center (AETC) of UMass in its educational efforts did help local high schools to build smaller versions of solar powered cars and the schools participated in open US competition of solar vehicles. In the following part we describe the design and testing of solar/electric cart which was built at Nashoba Valley Technical High School by UMass students with help of eleven-graders of that school. It is difficult to underestimate educational aspect of participation of high school students in design of machinery so complex as solar/electric cart.

We present the solar/electric cart capable of running at 30 mile/hour speed. The cart can carry 4 passengers and move attached additional load of about 500 kg. The battery block consists of a LiFePO₄...
cells and provides 6000 Watt power to 4 hub motor wheels, each rated at 1500 Watt. The 600 Watt solar array secured on the roof provides steady recharging for the lithium-ion batteries.

2. Fabrication of first prototype

Table 1 summarizes the list of the materials and components along with gross expenditure associated with them. To obviate relatively safe operation at low speeds and address the concern for reducing the curb weight of the vehicle, sheet aluminium was chosen as the basic material for fabrication of chassis of the car. The components were finally assembled together to realize the final product shown in Fig.1.

| Component and Rating                      | Quantity | Weight       | Price  |
|------------------------------------------|----------|--------------|--------|
| LiFePO₄ Battery Module (100Ah, 50V)      | 1        | 54kg         | $3000  |
| Battery Management System                | 1        | 1kg          | $1000  |
| Tire                                     | 4        | 35kg (approx.) | $140   |
| BLDC Hub motors                          | 4        | 14kg         | $400   |
| Kelly controller                         | 4        | 2kg          | $280   |
| Solar Panels 150W                        | 4        | 40kg         | $600   |
| Body (sheet aluminium)                   | 1        | 5kg          | $300   |
| Miscellaneous                            | NA       | 25kg         | $1000  |
| **Total**                                |          | **176kg**    | **$5,700** |

The electrical system of the vehicle is split into two main harnesses - power and control as shown in Fig.2. The power harness or the drive train begins with a 600 Watt solar array secured on the roof which is then connected to a battery through a solar MPPT charge controller.

The battery block consists of LiFePO₄ cells. The choice has been made considering the best trade-off between energy and power density as summarized in [5], while addressing the concerns of total weight and cost effectiveness other modules include battery management and balancing system, main switch, as well as controller pre-charge and safety circuits. The power is then distributed to four 1500 Watt hub motors via the respective motor controllers. Several variations of this power harness setup are possible, however they will all contain these key sub-blocks.
2.1. Implementation of electronic differential speed control

In accordance with the analysis conducted in [6-7], implementation of differential transmission by electronic means can allow for improved efficiency and decreased abrasion of mechanical components that are otherwise used in mechanical design of differential transmission. Therefore, the control harness consists of a central microcontroller circuit, which takes throttle and steering positions as inputs, calculates the speed multiplier of each wheel and sends the respective signals to each motor controller.

![Figure 2](image)

**Figure 2.** Schematic representation power and control system of the cart

Multipliers are necessary because all four wheels are on individual axes and should rotate at different speeds when the vehicle is turning. This electronic differential has been implemented to avoid skidding by accounting the differences in turning radii for the two sets of wheels.

3. Analysis of performance during test drive and future work

Performance of the vehicle in terms of speed, acceleration and power density of the battery were assessed in the first stage of test drive. Solar panels were disconnected from the batteries and the vehicle was driven around in a 1 acre parking lot. Use of Li ion cells with high energy density of the order 92.5Wh/kg, demonstrated satisfactory output performance for output power during the first of experimental test drive as it achieved reasonable performance in terms of speed of 10 mph and satisfactory acceleration. Based on these results evaluations of energy equilibrium and sustainability have been made. As explained in [8], the total traction effort required for electric vehicle can be expressed as-

\[ TTE = RR + GR + FA \] (1)
Where TTE is the total tractive effort, RR = rolling resistance, GR = Grade Resistance and FA = acceleration force. These terms are further elaborated as:

\[
RR = GVW \times Crr \\
GR = GVW \times \sin \theta \\
FA = Ma
\]

Where GVW = Gross Vehicle Weight, Crr = Coefficient of rolling resistance, \( \theta \) = angle of inclination of terrain and a = acceleration of the vehicle. Assuming concrete and asphalt based terrain for the vehicle the value of Crr has been finalized at 0.015. The average gradient in New England region is 0.25 therefore the value of \( \theta = 14^\circ \). From test drive results the value of acceleration for power harness of the vehicle was averaged at 0.499m/s\(^2\). Calculations were done while considering occupation of the vehicle by four individuals weighing 300kg in totality and a 1km long drive cycle that includes- 80m of acceleration, 100 meters of climb on inclined terrain and 820m of rolling on horizontal surface. The average tractive effort is found out to be 201.825N. 5kWh storage capacity within battery module makes the vehicle capable of covering 89km (55 miles) while consuming 89Wh/mile in a single cycle of charge. Considering the daily average of 4 hours for peaking of solar irradiance in Massachusetts, 2.4kWh of energy can be stored from solar irradiance on a daily basis. The motivating results have driven us to look for ways of enhancing the reliability in terms of energy efficiency and balance. Our experience with design of solar cart for small range off-road applications, has drawn us towards the idea of realizing the final prototype by optimizing three inter-dependent parameters. These metrics include- torque, energy balance and overall curb weight of the vehicle. While improvement of torque to weight ratio has enhanced performance of the vehicle, it must not compromise with energy density of the energy storage module.

Mounting of solar panels on the roof-top of the cart can potentially hamper generation during non-peak sun hours due to low angles of elevation associated with solar irradiance at higher latitudes associated with the New England region of the US. While limited area for solar panel installation and concerns for ergonomic operation eliminate possibility for use of solar trackers, use of curved mirrors operating in a manner similar to parabolic troughs [9], is slated for adoption. The height of the mirrors above the roof can be adjusted in accordance with solar angle at any time during the day.

Regular requirement of braking and limited power requirement in the driving cycle of the car for off-road environments increases the scope for regenerative braking. Therefore, it is set to be the next technological modification in the drive train of the cart. Although works related to implementation and modelling of regenerative braking for brushless DC motors is quite limited [10-11], cost effective technologies can be realized given the small scale of power associated with our application.

### 4. Conclusion

The first version of the manufacturable prototype of the vehicle has been realized by minimizing the weight of the vehicle and optimizing the output tractive power. This factor has played a major role ensuring energy balance and reduced dependence on grid supply for recharging. All raw materials were acquired at retail prices. Upscaled manufacturing is set to bring down the cost of material acquisition. Also, with increased penetration of lithium-ion batteries in the sectors of renewable energy and electric vehicles, their cost has plummeted to USD 100/kWh in 2020 and is set to be lower than USD 75/kWh by the end of the is decade [12]. The current rate significantly reduces the cost of energy storage in our prototype to $500 (USD) and the present value of our prototype to $3200 (USD). In the US, labor costs in automobile manufacturing industry account for 15% of the final cost which can potentially hike up our figure to $3800 [13]. Our final estimate can be rounded off to USD $4000 for the present value after factoring in costs for licensing and certification of the commercially available product.

This estimate alone can potentially compete with existing gasoline powered carts in the market which are priced at an average cost of USD $7000. On the other hand, the fully electric golf carts in the current American market are priced at USD $11000. On top of it, manufacturing costs of these vehicles can effectively be reduced by means of more efficient and cost-effective Design for Manufacturing techniques (DFM).
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