Designing a Concentrating Photovoltaic (CPV) system in adjunct with a silicon photovoltaic panel for a solar competition car

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ABSTRACT

Solar competition cars are a very interesting research laboratory for the development of new technologies heading to their further implementation in either commercial passenger vehicles or related applications. Besides, worldwide competitions allow the spreading of such ideas where the best and experienced teams bet on innovation and leading edge technologies, in order to develop more efficient vehicles. In these vehicles, some aspects generally make the difference such as aerodynamics, shape, weight, wheels and the main solar panels. Therefore, seeking to innovate in a competitive advantage, the first Colombian solar vehicle "Primavera", competitor at the World Solar Challenge (WSC)-2013, has implemented the usage of a Concentrating Photovoltaic (CPV) system as a complementary solar energy module to the common silicon photovoltaic panel. By harvesting sunlight with concentrating optical devices, CPVs are capable of maximizing the allowable photovoltaic area. However, the entire CPV system weight must be less harmful than the benefit of the extra electric energy generated, which in adjunct with added manufacture and design complexity, has intervened in the fact that CPVs had never been implemented in a solar car in such a scale as the one described in this work. Design considerations, the system development process and implementation are presented in this document considering both the restrictions of the context and the interaction of the CPV system with the solar car setup. The measured data evidences the advantage of using this complementary system during the competition and the potential this technology has for further developments.

Keywords: Concentrating Photovoltaic (CPV), solar car, Primavera, World Solar Challenge (WSC), Fresnel lens, gallium photovoltaic cell

1. INTRODUCTION

With annual sun radiation as high as 2100 kwh/m^2 in certain territories [1], Colombia has a great potential in terms of solar clean energy. However, solar solutions are not spreading as fast as they could in developing countries, presumably because most of the products have to be imported raising costs, and due to potential clients unwilling to trust a new technology. Therefore, a project such as the first Colombian solar car, so-called "Primavera", competing in the World Solar Challenge (WSC)-2013 [2] has the background goal of catalyzing local solar industry and inspiring Colombian people into believing in these sustainable technologies.

The World Solar Challenge is considered to be among the most important sustainable vehicle events in the world. Since 1987, teams from all over the world cross Australia from north to south in solar cars, taking their vehicles beyond the limits of efficiency. Innovation has always been one of the pillars of the spirit of the competition, especially in the category Primavera was designed for, so-called Challenger. Being this the most demanding category, the vehicles are constrained in terms of dimensions, number of wheels, photovoltaic (PV) area and are allowed to use only one initial direct battery charge, among other restrictions. Even though the World Solar Challenge is a 3000km long race, the high level of leading edge technological development and competitiveness, implies that every saved race minute is crucial and could mean the difference among the first positions. In such a long pathway, average speed is the key, and with most of the top teams being already highly efficient in terms of energy consumption, a suitable approach is to focus on generating more energy to be spent in higher speeds. Based on that premise, the Primavera team strategy to use concentrating photovoltaics (CPV) had a main goal of increasing the total solar energy harvested and transformed into electrical energy, without negatively affecting the vehicle performance and complying with the WSC-2013´s regulations [2]. This work describes how the CPVs design and development process was conducted correlating optical applications, solar power technology and manufacturing in order to overcome the drawbacks and reach a positive outcome.

2. STATE OF THE ART

2.1 Unconventional concentrating photovoltaic approaches

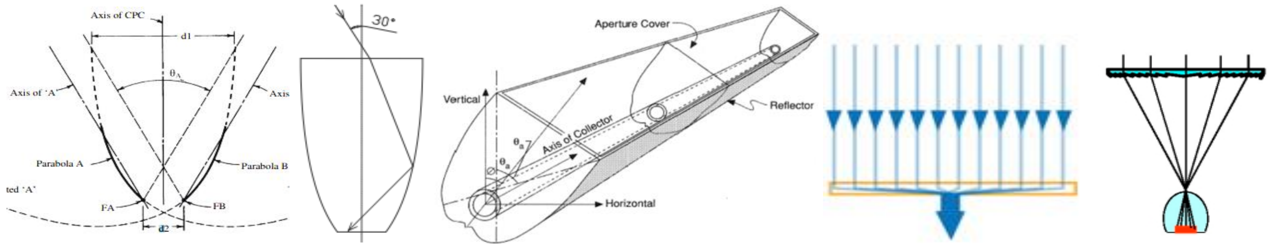
The following are several unconventional approaches to solar concentrating systems found in the academic and commercial state of the art.

Figure 1(a) and Figure 1(b) consist in a low compound parabolic mirrors concentrating approach [3] [4]. As the number of concentrated suns increases, the angle of acceptance in solar tracking declines. However, this approach can raise the angle of acceptance concerning the incoming solar rays as shown in Figure 1(b).

Figure 1(c) shows a medium compound parabolic mirrors device [5], which can be designed to have a broader angle of acceptance compared to the previous approach shown. However, the bouncing solar rays, presented in Figure 1(c), converge in a suspended line, which can lead to impracticality for photovoltaic cells.

The concentrating device in Figure 1(d), provided by Morgan Solar, can harvest and refract sunlight towards a photovoltaic cell with an up to 900 suns concentration rate. This device is supposed to remain unaltered by the temperatures that can be reached and is visually compact [6].

The refraction that takes place in the secondary optic element (SOE) [7] shown in Figure 1(e), redirects the sunlight rays coming from a range of directions towards the photovoltaic cell underneath. In adjunct with a Fresnel lens, this approach can keep generating energy even when not fully aligned towards the sun. Nevertheless, there is a considerable increase in height compared to using the Fresnel lens alone.



(a) (b) (c) (d) (e)

Figure 1. Unconventional concentrating photovoltaic approaches [3] [4] [5] [6] [7].

2.2 Concentrating photovoltaics in solar cars

In spite uncommon, there have been several teams that have used CPVs in their solar cars during the World Solar Challenge. The most representative examples are briefly described next.

Below on Figure 2(a), Michigan 2007 Continuum solar car is shown using its CPVs exposed in the upper surface. These CPVs consisted of reflecting mirrors, presumably linear parabolic mirrors, that could work during the static stages and while the car was moving due to an active tracking system that could pivot the CPVs to face the sun within a certain range. On Figure 2(b), the 2009 Michigan car Infinium can be seen using static CPVs, which could work only when the upper bodywork was removed while the car wasn’t moving, and in order for them to face the sun, the entire lower bodywork had to be tilted.

Figure 2(c) consists of the 2007 Solar Team Twente car tilting its upper bodywork while moving for the main panels to face the sun as much as possible, and for the CPVs to work. The CPV system uses linear Fresnel lenses to focus sunlight into rows of solar cells underneath. Moreover, the rows of solar cells could move by using electric actuators for them to follow the focused lines when the tilting system reached its functional limits [9].

(a) (b) (c)

Figure 2. Previous implementations of CPVs in solar competition cars [8] [9].

3. DESIGN PROCESS

Following the CPVs main goal, the design process focused on maximizing the net income of energy measured in Watts into the battery pack. Showing the related variables and the way they affect the final result, the authors summarize the approach into the following equation, serving a as a guide for the entire design process.

$$E = (A_c * S * R * \eta_c * \eta_{ot} * \eta_s * N_{CPV} * t_{CPV}) - \left((P_{lw} * t_{sv}) + (P_{lc} * t_{cc})\right) \qquad (1)$$

With $E =$ net income of energy $[W]$; $A_c =$ PV area $[m^2]$ of a single solar cell; $S =$ Number of concentrated suns; R = incoming solar radiation $[(W/h)/m^2]$; $\eta_c =$ Solar cells efficiency; $\eta_{ot} =$ Optical technology efficiency, $\eta_s =$ System efficiency (taking into account electric connections and MPPT efficiency among others); $N_{CPV} =$ Number of CPVs; $t_{CPV} =$ Time $[h]$ using the CPVs; $P_{lw} =$ Power losses $[(W/h)]$ due to the CPV system weight increase in the rolling resistance; $t_{sv} =$ Time $[h]$ moving the vehicle by its own power supply; $P_{lc} =$ Direct power consumption $[(W/h)]$ due to the CPV system energy consuming components, such as fans or pumps; and $t_{cc} =$ Time $[h]$ using energy consuming components of the CPV system.

After choosing the concentrating technology according to the design requirements, the physical variables were defined in a progressive process including the size of the solar cells, the total PV area, the optical devices area, the CPVs height, the number of concentrated suns, and the number of CPVs. Afterwards, the detailed design was carried out and improved in terms of weight, manufacturability and performance through three prototypes. Finally, the CPVs were designed as a system, comprising the distribution, the electric circuit, the tracking and cooling strategy, and the safety considerations.

3.1 Design requirements

Designing a CPV array for a solar car, meant to compete in a world class race, is a challenging and complex process due to all regulations and specifications that it must meet. In the first place, the system must produce more energy than the energy consumed due to its weight and its electronics. In order for this to be accomplished, early simulations were performed in a Strategy-Simulation-Software (3S)[1] in which different weights for the CPV array were assumed and possible total power generations were calculated. The balance, on which the CPV viability relies on, depends on the trade-off on energy harvested by the CPVs versus the extra-energy that the CPV system will demand principally because of the extra weight added to the vehicle, which increases the rolling resistance. If the energy harvested by the CPVs is lower than the extra energy consumed by the vehicle because of the CPVs system, then the system is not viable. A preliminary analysis performed with the 3S program showed that the extra energy obtained because of the CPV system could save approximately 20 race minutes. Thus, the entire CPV system shouldn't exceed 20Kg taking into account that every extra Kg increments in a minute the time necessary to finish the race.

Even if the CPV system reached a positive ratio of cost/benefit, it should also meet all requirements stated in the World Solar Challenge 2013 regulations [2]. WSC-2013's regulations constrain the maximum photovoltaic (PV) area, but don't limit its usage exclusively for the main solar panel, making it possible for the PV area to be distributed among the main solar panel and a CPV system. Moreover, the CPV design process was carried out always taking into account all other relating regulations, such as not interfering with the pilot performing an emergency exit.

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[1] The Strategy-Simulation-Software is a custom made application developed in Python to predict the overall energy management system of the vehicle, considering the energy harvesting (Panel+CPVs), storage (Battery) and consumption, in order to strategically plan all race decisions such as speed and stops, among others.

Since CPV performance is subjected to direct sunlight and a precise sun tracking, it was considered neither practical, nor strategic to locate them exposed in the upper surface subtracting area from the main solar panel. Instead, the Primavera concentrators were planned to remain under the main exposed solar panel until the static stages of the race, when the upper bodywork is removed to be tilted towards the sun and thus, exposing the CPV systems beneath. Therefore, the entire system should fit inside the slim and aerodynamic bodywork, making the CPVs height crucial since it is inversely proportional to the number of CPVs that could fit. Likewise, the system needed to be rigid and stiff enough to resist being in a moving vehicle, its materials ought to resist the desert temperatures (up to 40°C) and temperature raise due to concentrating sunlight (Over 70°C) and the system should not compromise the security by, for instance, starting a fire. Furthermore, a tracking and cooling strategy was necessary for the system to be efficient and competitive. In terms of the CPVs as individual units, manufacturability and design simplicity were essential to ensure meeting all the requirements with precision and reliability, given that the budget, workforce and implementation time were limited.

3.2 Chosen concentrating approach

Having analyzed all conventional and unconventional approaches, the chosen concentrating technology were the Punctual Fresnel Lenses. As shown in Figure 3, this optical element consists in a lens that has a stepped curvature which refracts the incoming rays (perpendicular to a central plane) into a common focal point.

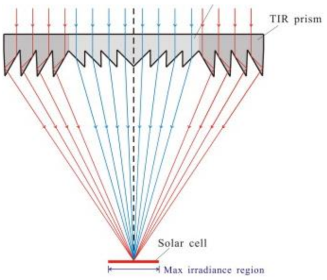


Figure 3. CPV scheme with a Fresnel lens-solar cell configuration. [10]

The advantages compared to other concentrating approaches are the following:

- Compared to regular lenses, Fresnels are lighter, less expensive, more compact and easier to manufacture.
- There is a wide commercial availability of Fresnel lenses of all sorts of sizes and focal lengths contributing to the design flexibility.
- From a general perspective, this solution had the potential of getting to a simpler and more manufacturable overall design.

3.3 Physical variables definition

The process of defining all physical variables of the design was a progressive development from two different approaches. From one side, there was an approximate process of preliminary calculations and CAD (Computer Aided Design) volume simulations based on general assumptions, provided that some variables depended on each other such as height and number of CPVs, so there was not a single possible solution. From the other side, there was a process of selection between available and suitable commercial elements. The convergence between these two approaches defined the physical variables of the three developed prototypes shown in Figures 7(a), 7(b) and 7(c).

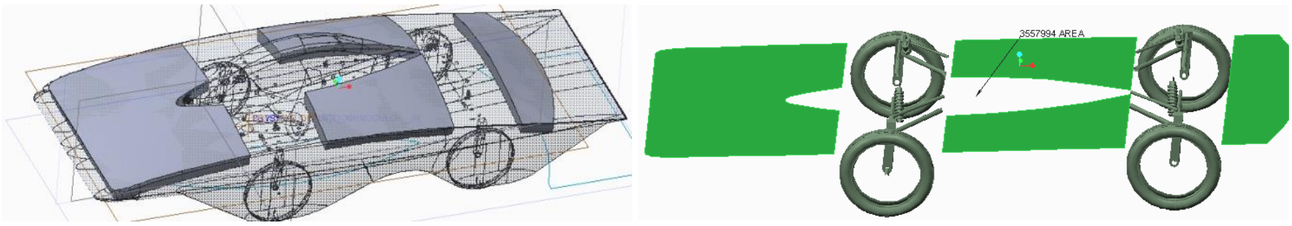
3.3.1 Areas and number of CPVs

The WSC-2013´s regulations stated a mathematical relation between Silicon (Si) and Gallium (Ga) photovoltaic area, where

$$A_{Ga} = 3 * \left(1 - \left(\frac{A_{Si}}{6}\right)\right) \qquad (2)$$

with A_{Ga}=Gallium Area and A_{Si}=Silicon Area. Since the Ga is more efficient, the regulations limit its use and the bigger the Ga area, the smaller the total photovoltaic allowable area. The main Silicon panel had a 5.796m^2 area, limited by the maximum photovoltaic area (6 m^2), the aerodynamic design and the regulated maximum dimensions. This meant an allowable extra 0.102m^2 Ga area, or 0.204m^2 Si area that could be used in the CPV photovoltaic cells. For CPVs, Ga was chosen because of its superior efficiency (usually >30% efficiency) [11], for its capability to increase its efficiency (under a physical limit) as the number of concentrated suns rises and for it being able to resist higher concentrations (>1000 suns) [12] as well as higher temperatures.

After analyzing available commercial Fresnel lenses, the research focused on the Edmund Optics supplier [13], being a reference of cost/quality. A potential height for the CPVs was assumed to be of 10-13 cm and, starting from that, a preliminary CAD volume simulation was performed. The image in Figure 4(a) shows how some sections were trimmed from the volume simulation to avoid collisions with other systems, the bodywork and the cockpit. Since the Fresnel lenses are flat and should be in parallel planes, the upper curved surface of the simulated volume was flattened and measured. Figure 4(b) shows the resulting preliminary available area for the CPVs of 3, 56 m^2. Since the widest elements of the CPVs are the Fresnel lenses, this area can be taken as the maximum area for all lenses together.



(a) (b)

Figure 4. CPVs initial vol[illegible] emulations in CAD model and available area for the CPVs.

Having defined to use Ga cells, an issue of availability arose. Ga is a material usually reserved for aerospace applications and high efficiency CPV power stations (solar farms). Additionally, it was experimentally found that cutting a solar cell and rebuilding its micro-connections implied a level of complexity that should be avoided if possible. Therefore, it was decided to use available GreenVolts modules [14] which came with 5.5x5.5 mm Ga cells embedded in their own circuit with diode. With an allowable 0.102 m^2 Ga area, it would then be possible to locate 3371 CPVs, each one with a 0.00003025 m^2 Ga area. In this configuration, if the whole lens available area of 3,56 m^2 were to be used, each lens would have a concentrating rate of 34,9 suns. However, since Ga cells raise their efficiency considerably in high concentration rates and the GreenVolts modules were designed to work under as high as 1300suns, the CPVs configuration was defined for a desired concentrating rate. To leave a margin from operational specifications, but still having high concentrating rates, the desired concentration was established to be close from 1000 suns and overlapping that with the information of available commercial Fresnel Lenses, the concentrating rate was set to be of 1107 suns.

Consequently, as

$$X = \left(\frac{A_L}{A_C}\right) \tag{3}$$

With X=concentrated suns, A_L=Lens area and A_C=Solar cell photovoltaic area, each lens would then have a 0,03348 m^2 area with dimensions of 182,9 mm x 182,9 mm since they would be cut in a square shape. Moreover, this equation means that with 3, 56m^2 of lens area, there would be 0,0032m^2 of Ga photovoltaic area distributed among 106 CPVs.

3.3.2 CPVs height

At first, the height of the CPVs was calculated by entering the focal length stated by the supplier in a 2D simulation using CAD Software. For instance, Figure 5 shows an example of an approximate resulting CPV height of 7,96 mm providing a focal length of 10,16 mm. The method of entering the focal length stated by the supplier experimentally validated. Tests showed that the real focal length was in fact different from supplier's specification.

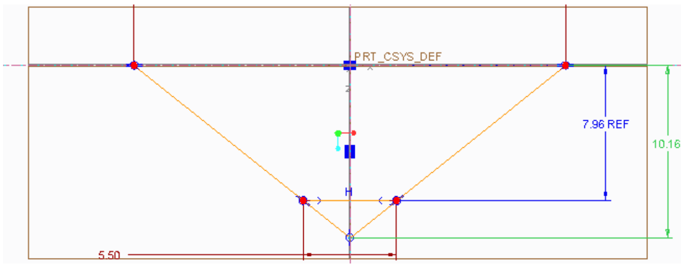


Figure 5. Height calculation of a CPV using Creo Parametric 2.0.

Figure 6 illustrates a device with variable height designed to find the distance between the lens and the cell which resulted in the best combination of Amperage and Voltage. This method was used for defining the heights of the three CPV prototypes developed.

Figure 6. Device designed to experimentally find the most suitable distance between a Fresnel lens and a photovoltaic cell.

3.4 Prototypes

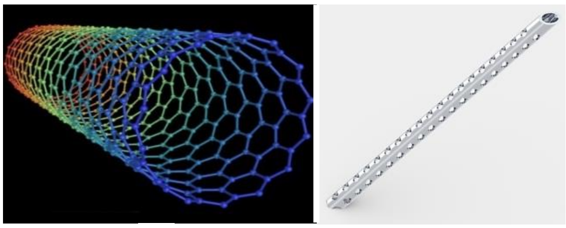
To get to the final design, the CPVs of Primavera evolved through three prototypes shown in Figure 7. The first prototype shown in Figure 7(a), succeeded in structurality and in accuracy converging the sun rays into the photovoltaic cell. However, there were two issues involved that consisted in the numerous steps required to manufacture each CPV, and the high weight. With each CPV weighting 189.7 g, the 106 CPVs would weight 20.11 Kg overpassing the initial weight limit without even taking into account other elements required for the CPV array, such as the MMPT or CPVs chassis. Being not possible to reduce the lens weight, which represented the 36.9% of the total weight, the second prototype shown in Figure 7(b), focused on reducing the weight of the other parts and reducing the manufacture steps. After reaching an acceptable weight and manufacturability, the prototype-3, shown in 7(c), was developed to increase the performance solving certain optical issues described in the following subsections.

(a) (b) (c)

Figure 7. CAD lateral views, CAD renderings and photos of prototypes 1, 2 and 3.

3.4.1 Prototype-2 weight reduction

As can be seen in figure 8, the columns were redesigned, as seen in Figure 8(b), inspired by the carbon nanotubes atomic structure shown in Figure 8(a), which plays a key role in the superlative stiffness of the material while being notoriously light. The four columns, which represented the 28.62% of the total weight, went from 54.3 g to 26 g, reaching a 52.12% weight reduction in columns.



(a) (b)

Figure 8. The final column design inspired by the carbon nanotube atomic structure [15] [16].

The screws and nuts were replaced by acrylic resin, going from 9 g to 0.3 g, obtaining a 96.66% weight reduction in fastener elements. Moreover, the base was reduced as much as possible decreasing its weight in 27.2%. These evolutions were obtained by improving prototype-1, achieving prototype-2. The overall weight reduction resulting from this step can be viewed in table 1.

Table 1. Comparison between the weight of prototype-1 and prototype-2 as individual units and as the whole array.

Prototype1	Prototype2	Weight reduction	CPVs Array1	CPVs Array2	Total Weight Reduction
189.7g	137.5g	52.2g-27.5 %	20.108Kg	14.57Kg	5.54Kg

3.4.2 Prototype-2 power generation analysis

Having achieved the weight reduction goal, the next step was to assure that the amount of power generated by the CPVs was enough to justify their use in the vehicle. Several tests with the prototype-2 showed that the CPV was not producing what it was supposed to, based on control tests as it is evidenced in table 2.

Table 2. CPV prototypes 1 and 2 comparison in terms of performance.

Prototype-2			Control Test		
Open-circuit voltage (V_{OC})	Short-circuit current (I_{sc})	$(V_{OC})*(I_{sc})$	Open-circuit voltage (V_{OC})	Short-circuit current (I_{sc})	$(V_{OC})*(I_{sc})$
2.9 V	0.37 A	1.07 Watts	2.96V	1.5 A	4.44 Watts

It is important to clarify that $(V_{OC})*(I_{sc})$ is not equal to the real power generated due to the power generation curve inherent to photovoltaic cells, but it is useful to make comparisons and is referred in this work as “Comparative Power”. The control test was carried out using a GreenVolts module just as the one that Prototype-1 and Prototype-2 used but using a different Fresnel lens with a bigger focal length and at different distances between the solar cell and the lens. The control test produced 413.8% of the Comparative Power produced by prototype-2, suggesting that there were optical issues involved in the prototype design.

Several experimental tests studying laser trajectories revealed the causes of the low Comparative Power generation:

- The used Fresnel Lenses, as they were not specifically designed for solar concentration, didn’t converge light in a single focal point as it was assumed to, but in two different focal points vertically apart from each other. Consequently, the light entering the GreenVolts module were the rays being converged to only one of the two focal points thus, the rest of the rays were not reaching the solar cell.
- The GreenVolts module used a secondary lens over the solar cell which had an angle range of admission. This angle range was found to be of approximately 26° from the vertical axis and was being surpassed by a portion of the rays

converged by the used Fresnel lenses. Therefore, all rays converged over the 26° could be reaching the GreenVolts secondary lens but not reaching the solar cell underneath.

3.4.3 Improvements to obtain the final design (Prototype-3)

The final design, reached in the prototype-3 shown in Figure 7(c), consisted mainly in solving the optical issues found in the power generation analysis and improving the design for manufacture of the base, in terms of required number of manufacturing steps and their involved difficulty.

Knowing that the previous Fresnel lenses were not meant to be used for concentration, it was defined to use other lenses specially designed for CPVs from the supplier Fresnel Factory. These lenses, with the reference CP182-235, were stated to be capable of converging the perpendicularly incoming rays into a common focal point with a high efficiency. Nevertheless, they had a longer focal length, going from 70mm in the previous lenses to 182mm, which caused the CPVs height to increase considerably. Moreover, the secondary lens was removed from the design to avoid the issue concerning the angle range of admission. This decision was verified with experimental tests which showed an increase in Comparative Power generation whit the secondary lens removed.

The distance between the lens and the solar cell was recalculated with the experimental method described in the section 3.3.2 (CPVs height). This method led to the definition of the final proportions of the CPVs, where height went from 133.9 mm to 195.7 mm. With the increased height, the columns length increased as well. Also, the secondary lens was removed and the thickness of the lens changed from 3mm to 4mm. The previous changes resulted in an overall weight of 166.2 g per CPV.

3.4.4 Prototype-3 tests

In table 3, the data shown in Prototype-3 is the result of average measures among several tests performed under the real sun between 11:00 am – 2:00 pm. The results evidence the effects of the optical solutions implemented, since the Comparative Power generation increased in a 746.9%.

Table 3. CPV prototypes 2 and 3 comparison in terms of performance.

Prototype-2			Prototype-3		
Open-circuit voltage (V_{OC})	Short-circuit current (I_{sc})	(V_{OC})* (I_{sc})	Open-circuit voltage (V_{OC})	Short-circuit current (I_{sc})	(V_{OC})* (I_{sc})
2.9 V	0.37 A	1.07 Watts	2.96 V	3.07 A	9.09 Watts

3.5 CPVs design as a system

After assuring that the CPVs final design had a suitable weight, structurality and power generation, the next phase consisted in defining the details required to achieve a functional system for a solar racing car.

3.5.1 Distribution

With a final CAD model of the CPV design, the detailed distribution process was carried out assembling as many CPVs as possible without interfering with any other system, the bodywork or the cockpit. The following aspects were taken into account:

- All CPVs should be assembled in such a way that their lenses were all in parallel planes, so all the CPVs could be aligned facing the sun at the same time if the car were to be tilted towards the sun.
- The CPVs should be grouped in zones that would be rigid themselves but not between them. Each CPV independent from each other would result in a number of different modules too big to be installed and handled in a practical way, whereas all CPVs fixed rigidly together would suppose a big and heavy structure to be properly handled. Therefore, the strategy of dividing them in independent zones.
- Ideally, all CPVs should be positioned in the same height to simplify the design and installation. This was not possible to achieve due to the changing inner geometries of the vehicle, the heights should be grouped in, as few as possible, different heights.

Figure 9 shows how it was possible to fit 64 CPVs in 6 zones with 5 different heights plus a “floating CPV”. The floating CPV consisted in an additional module that could fit in the closed car by lying horizontally and that would then be turned to be vertical (aided by a rotating mechanism) once removed the upper bodywork. The floating CPV can be seen in the top view, located at the lower right corner.

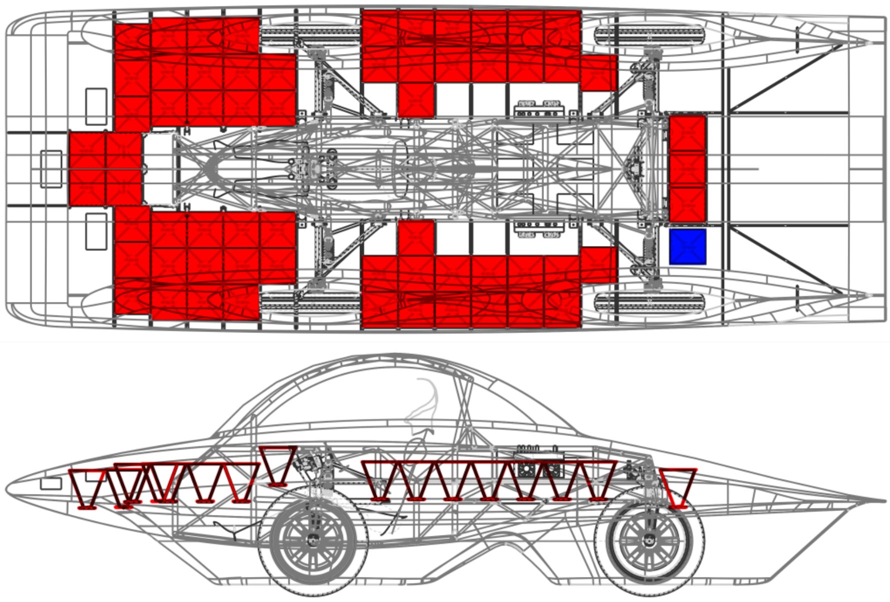


Figure 9. CPVs configuration inside of the solar car Primavera seen from top and side views.

3.5.2 Electric circuit

The 64 CPVs were connected by two circuit series each one of 32 CPVs. Both series were connected in parallel in a MPPT, which function was to regulate and configure the incoming voltage and current in order to deliver the highest power possible. The used MPPT had a functioning range of 36 V – 144 V, which was suitable for the expected 80 – 96 V voltage coming from the two series. Furthermore, most of the zones were independent series to simplify connectivity and zones installation in the vehicle.

3.5.3 Tracking strategy

In order for the CPVs to be able to generate electric power, the lenses must focus light into the photovoltaic cell, which is only possible when the incoming rays are perpendicular to the Fresnel lenses surface. The CPV system was designed to reside rigidly fixed to the car’s lower bodywork with all CPVs aligned in parallel planes. This way, the whole lower bodywork was supposed to be tilted to face the sun aided by an adjustable structure and light perpendicularity measuring devices. Even though it was possible to align and fix all CPVs with an error margin of 0.6 °, it was found experimentally that the bodywork rigidity was not enough to keep the CPVs aligned after regular testing of the car in a race track. Because of this, the tracking strategy changed into aligning each CPV zone individually by hand. Aided by special welding glasses, the team members could look directly at the focused light and verify if it was reaching the photovoltaic cells.

3.5.4 Cooling strategy

Under a midday sun, unconcentrated photovoltaic cells exceeded the 60°C during tests. At 1107 suns, the cells in the CPVs could easily exceed the 100°C. Even though Ga cells can perform well under high temperatures (as high as 100°C), the lower the temperature, the higher the efficiency. Therefore, to increase the efficiency and to reduce the risk of permanently damaging the Ga cells, a cooling strategy was carried out during the WSC-2013 race. While the CPVs were being used, dielectric water was atomized directly under the aluminum surface were the photovoltaic cell was. This alternative was the only option according to WSC-2013’s regulations about externail aids. The strategy was simple, yet effective.

3.5.5 Safety Strategy

While performing security tests, the focused sunlight coming from the used Fresnel lenses was capable to ignite Wood almost immediately. This situation can produce smoke from the material of the bodywork (carbon fiber with vinyl ester resin compound) and even from an anti-fire foam which was stated to resist over the 400°C. However, the CPVs were not able to degrade a Silica cloth which was capable of resisting 1000°C. Therefore, the temperature reached in the focal point was likely to be between 400°C-1000°C, enough to represent a real danger of fire inside or outside the vehicle. There is a 17° safety margin for misalignment, meaning that if the CPVs are tilted in a range of (-17°) to (17°) from total alignment towards the sun, the focus point will move but will still be focused in the aluminum plaque surrounding the solar cell, so it would not represent any danger to the car.

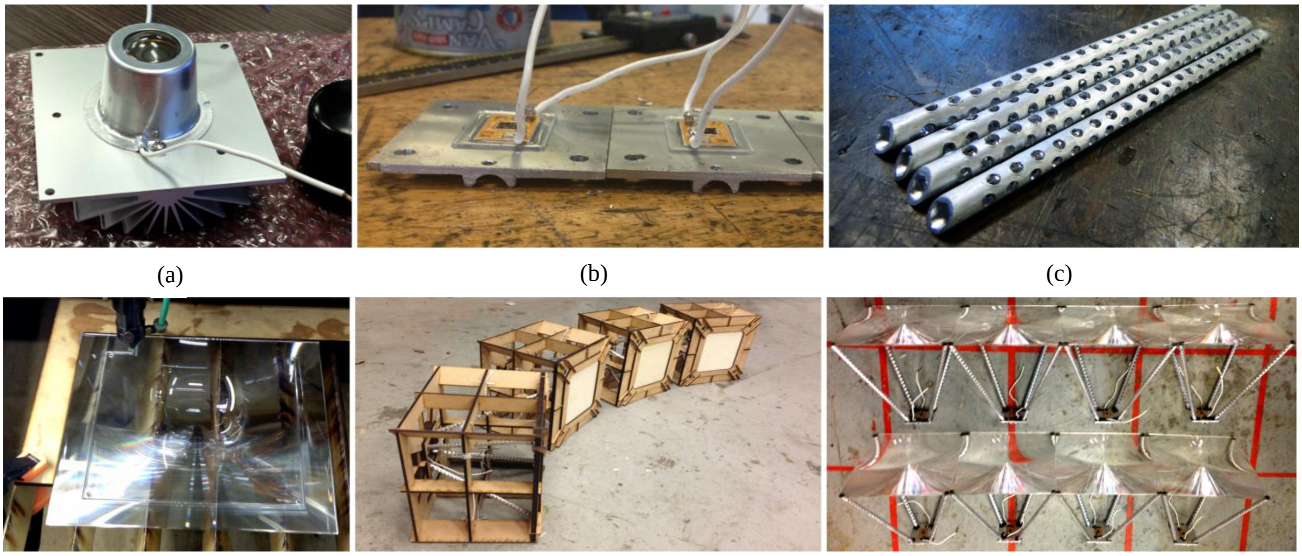
Even with the mentioned angle, when the top bodywork was removed, exposing the 64 CPVs, the incoming solar rays could surpass the 17° depending on the hour. To avoid danger, special reflective coverings were designed to rest over the CPV zones until they were outside of the car and close to being totally aligned to the sun.

4 IMPLEMENTATION

4.1 Manufacture

Figure 10 shows the main parts of the CPVs and the key milestones in manufacture of 75 units:

- Figure 10(a) shows the GreenVolts original concentrating modules, including a Ga cell embedded in a circuit with diode, an aluminum heat sink and a secondary lens within an aluminum casing.
- A removal material process was applied. Figure 10(b) shows how each module was milled into the final CPV bases, reducing volume and weight. Secondary lens and its casing was also removed.
- Figure 10(c) shows columns cut and drilled from 5/16" aluminum tubing.
- Original Fresnel lenses where cut into its final shape by CNC laser cutting, as seen in Figure 10(d).
- Being the assembly precision crucial for the lenses to focus the light into the Ga cell, the CPVs were fixed with acrylic resin aided by a jig that maintained the parts firmly aligned. Eight of these jigs were manufactured for several CPVs to be assembled and let curing in parallel as can be seen in Figure 10(e). This method proved to be successful since only 3 CPVs didn’t passed focus precision tests out of 74 tested.
- Figure 10(f) displays eight finished CPVs, from a total of 75 that were manufactured and assembled.


(a) (b) (c)

(d) (e) (f)

Figure 10. Main CPV parts and key processes concerning manufacture.

4.2 CPV Zones assembly

A lightweight aluminum chassis was developed for each zone to remain assembled together. For every zone, the CPVs were fixed between them and to their zone chassis using acrylic resin Scotch-Weld DP805. Since all CPVs of a zone were to be fixed in parallel planes, they were assembled with the resin while being face down over a flat glass with metal weights pressuring them against the flat surface.

4.3 Installation

64 CPVs were finally fitted into the vehicle, assembled to the lower bodywork and the main chassis (See Figure 11). All necessary adjustments were carried out for the CPVs not to interfere with other parts and systems, such as reducing the upper bodywork ribs height.

Figure 11. Exposed CPVs assembled in Primavera solar car.

4.4 World Solar Challenge 2013

Figure 12 illustrates three CPV zones being used during a control stop with the main solar panel facing the sun as well in the background.

Figure 12. CPVs being used during the WSC-2013.

According to the WSC-2013´s regulations, the solar cars are allowed to race after 8:00 am and until 5:00 pm. Since the CPVs could work only while not moving, they were used from the sunrise (around 6:00am on average) until 8:00 am and from 5:00 pm until sunset (around 6:25 pm on average). Additionally the mandatory control stops, which were of 30min each, were the opportunity to deploy the CPVs.

5 RESULTS AND ANALYSIS

The entire CPV system including the 64 CPVs, the zones chassis, the electric cables and the MPPT, weighed approximately 15kg. Considering the initial goal of 20kg, the system represented the 75% of the allowable weight.

The graph shown in Figure 13 depicts the power generated in Watts (Y axis) throughout the race days (X axis as time). The total power generated by the main solar panel and the CPVs, can be viewed in the peaks that rise higher in power, and the power generated only by the CPVs is represented by the lower line. Although the race lasted 6 days, the power generation information could not be stored during the first days due to telemetry issues. Therefore, the data showed are from days 3 to 6.

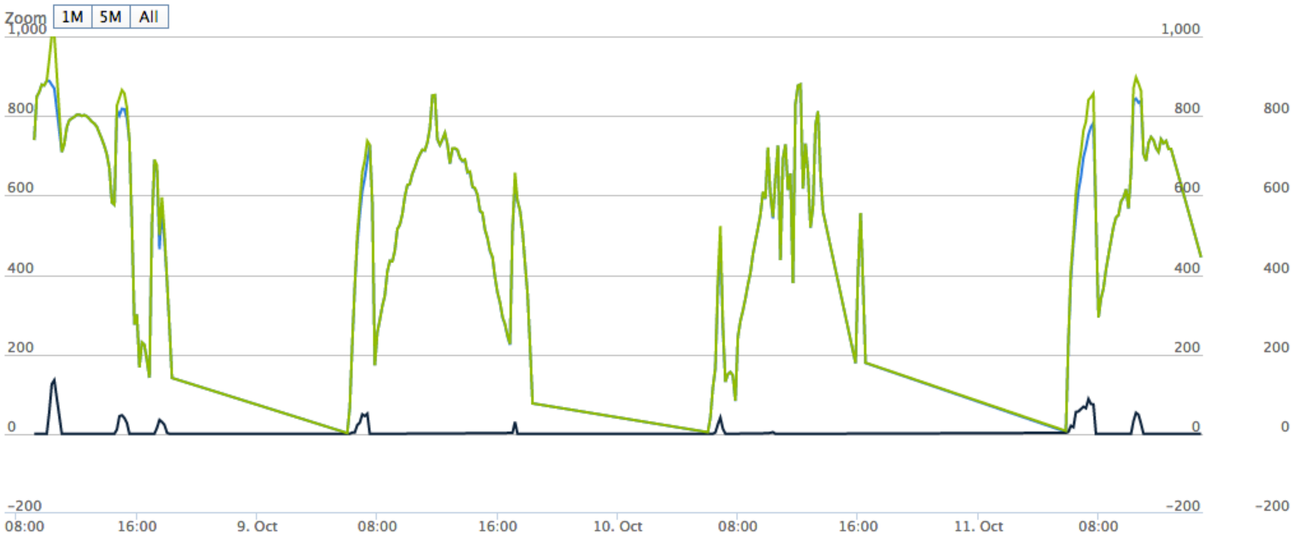


Figure 13. Power generation chart during race days concerning the main solar power and the CPV array.

From Figure 13 it can be highlighted:

- Day 3: During the morning, the maximum CPV power generation reached 150Watts, which implied 15% of the power that was being generated by the main solar panel at that time. CPVs were used in the morning, evening and at a control point around 3:00 pm, when power generation raised higher than in the evening due to greater radiation being the sun higher in the sky.
- Day 4: Due to logistic issues, it was not possible to use the CPVs during the control stop. The CPV power peak was reached at 55Watts, representing the 7.5% of the power being generated by the main panel at that time.
- Day 5: The cloudy weather affected the CPVs performance, making it not possible to concentrate direct light in the evening. Without direct light, the CPVs are not capable of generating enough voltage to turn the MPPT on and thus, whatever power generated couldn't reach the battery. The maximum power generated was 50 Watts, the 9.53% of the power being generated by the main solar panel at that moment.
- Day 6: CPVs were used during the morning and in a control stop before the arrival to the finish line. The power generation reached a peak of 100Watts, 12% of the main solar panel power generation at that same time.

6 CONCLUSIONS

- With a weight of approximately 15kg, the entire system represented the 5.55% of the total weight of the vehicle without driver and managed to generate up to 15% of the energy generated by the main solar panel and thus, the 13.04% of the total energy generated by the vehicle. Furthermore, the photovoltaic area of the CPV array of

0,001936 m^2 implied only the 0.033% of the main panel area. The previous relations evidence the benefits of using concentrated photovoltaics, even though better performance could be achieved based on the individual CPV tests, which showed a maximum “Comparative Power Generation” of up to 10 Watts/CPV. Provided the prior definition of Comparative Power in this work, it could be assumed a potential 7 Watts/CPV, which would reach a total of 448 Watts for the entire array, being the 56% of the average power generation of the main panel. Therefore, the CPV system proved to be not only beneficial during WSC-2013, but also to have the potential of becoming a major competitive advantage in a further development.

- The design and development process succeeded in weight and resilience initial goals. With an approximate weight of 15kg, the system weighed 25% less than initially allowable. The CPV zones managed to keep working despite of more extreme conditions than what they were designed for, such as being manipulated over the dessert sand, held in the air manually and being constantly taken in and out of the vehicle while being in a hurry.
- Precision in CPV manufacture is crucial, for the lack of alignment between the concentrating optics and the solar cell can result in sunlight not reaching the photovoltaic surface and thus, in electric power not being generated. With only 3 out of 74 tested CPVs that didn’t pass light focus tests, the assembly technique of using wooden low cost jigs proved to be effective and accurate with a 96% success rate.
- The CPV performance results during the WSC-2013 evidenced the main drawback of using concentrated photovoltaic, which is its weather dependence. For instance, the cloudy weather of day 5 avoided direct sunlight to reach the CPVs. This resulted in the inability to power on the MPPT and thus, in no electric power generation while the main un-concentrated panel was generating up to 650Watts. Additionally, with a maximum relation of CPVs-Main panel of 15%, the CPVs could have theoretically generated up to 97.5Watts with direct sunlight.
- The major necessary changes in terms of tracking and main use strategy serve as an instance of the bodywork of a solar competition vehicle not being stiff enough to be rigidly fixed to a CPV array. Such a lack of stiffness resulted in the misalignment of the CPVs and, therefore, a tracking strategy independent from the bodywork structurality is seemingly more suitable.
- The CPVs being grouped in structurally independent zones showed to be highly advantageous for this feature made the system flexible enough to adapt to a considerably different use strategy. Both individual and single grouped CPVs would have been too difficult to handle outside of the vehicle in an efficient and practical way and this might have resulted in the system not being used at all.

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