Model Based Control of a Moving Solar Roof for a Solar Vehicle

G.Coraggio*, C.Pisanti*, G.Rizzo*, A.Senatore*

*Dept. Of Mechanical Engineering, University of Salerno, 84084 Fisciano (SA), Italy
Email: gcoraggio - cpisanti – grizzo – a.senatore @unisa.it

A study on the benefits and the control of a moving solar roof for parking phases in a solar assisted vehicle is presented. A small scale real prototype of this mobile roof has been realized as a parallel robot with three degrees of freedom, connected with three step motors, and experimental data have been made to validate the calculated results. The effects of roof design variables are analyzed, and the benefits in terms of net available energy assessed by simulation over hourly solar data at various months and latitudes. The structure of a control system for the solar roof is also presented. In order to maximise the solar contribution and to avoid unnecessary movements of the roof, the system is controlled by a combined use of measured solar power, image processing form a digital camera and data provided by a GPS module.

*Keywords***:** *Model Based Control, Tracking systems, Solar energy, Hybrid vehicles.*

1. INTRODUCTION

In last years an increasing attention is being paid to the integration of Hybrid Electric Vehicles (HEV) and Photo-Voltaic (PV) sources [1,2], as confirmed by the recent launch of a HEV mounting solar panels by a major automotive company. A great attention has also solar energy, because it is a kind of renewable, gratis and largely diffused energy. Thanks to the combination of this two elements is recently born the idea of Hybrid Solar Vehicles (HSV): these vehicles can give substantial benefits to fuel economy and emissions, especially in the case of intermittent use in urban driving [1-5]. Moreover, their economic feasibility may be achieved in a near future, thanks to the decreasing cost (Fig. 1) and to the increasing efficiency of photovoltaic panels and the increasing cost of traditional fuels.

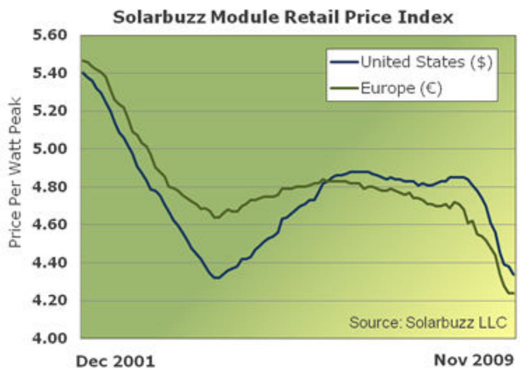

Fig. 1 – Trends in photovoltaic panels price

The additional costs of HSV with respect to HEV are mainly due to photovoltaic panels, that in solar cars are used at fixed, almost horizontal, position. As known, the amount of direct solar energy captured by the surface depends on the angle of incidence (Fig. 2) [7], defined as the angle between sun rays and the perpendicular to the surface:

$$E_c = E_i \cdot \cos i \qquad (1)$$

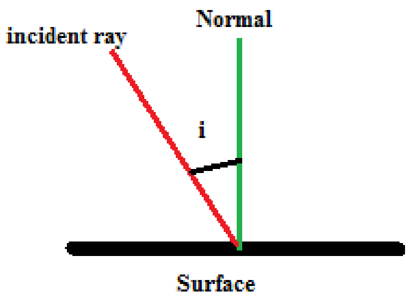

Fig. 2 – Angle of incidence

Although in last years different solutions of moving panels are being adopted in fixed photovoltaic plants, this option has not been considered until now on solar cars, where PV panels are fixed and located in an almost horizontal position. In pure solar cars, that have no or little storage capacity, the instability and the aerodynamic losses related to the use of a moving roof during driving would not compensate their benefits. Moreover, the energy spent to orient the panel during driving can be much greater that the energy required on a fixed plant, if car orientation is often varying.

The picture can be different if moving solar panels are adopted on an electric or a hybrid vehicle, provided with a battery of adequate capacity. Previous studies, as well as simple energy balances, demonstrate that the relative benefits of solar energy are quite significant (up to 30%) when the car is used for one or two hours per day in urban driving, as it happens for a large number of users [2-5]. In this case, a large part of the solar energy is captured during parking time, and the adoption of a tracking system just when the car is parked would not cause a negative impact on vehicle stability and aerodynamics. On the other hand, there are some specific aspects that make the study of a moving roof on a car, even if only when parked, different from a fixed plant, since: i) car orientation during parking is not fixed, ii) additional weight should be minimized, iii) perfect orientation toward the sun could not be achieved in all conditions due to kinematic constraints.

The effects of roof orientation can be estimated by a solar calculator, based on the analysis of time series of solar radiation in US cities over about 30 years [www.nrel.gov/rredc/pvwatts]. The results, presented in Fig. 3, show that the adoption of a perfectly oriented solar panel can give a substantial improvement in the annual solar energy with respect to the horizontal position, particularly at high latitudes.

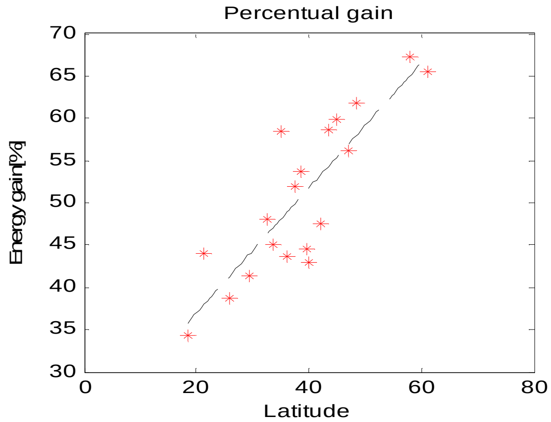

Fig. 3 - Gain in yearly solar energy of a two-axis tracking PV array with respect to a fixed one (horizontal)

The abovementioned results are referred to a fixed plant, while in case of a mobile roof on a vehicle the increase in collected energy is extended only to parking time.

2. THE MOBILE SOLAR ROOF

A moving solar roof as a parallel robot with three degrees of freedom [8] has been recently proposed by the authors [6].

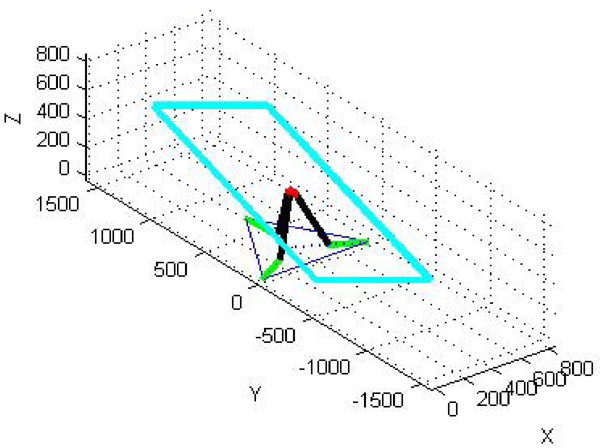

Fig. 4 - The model of moving roof realized with Matlab

A kinematic model, implemented in Matlab (Fig. 4) and Solid Works (Fig. 5), has been validated over the experimental data obtained by a small scale real prototype developed at the University of Salerno (Fig. 6).

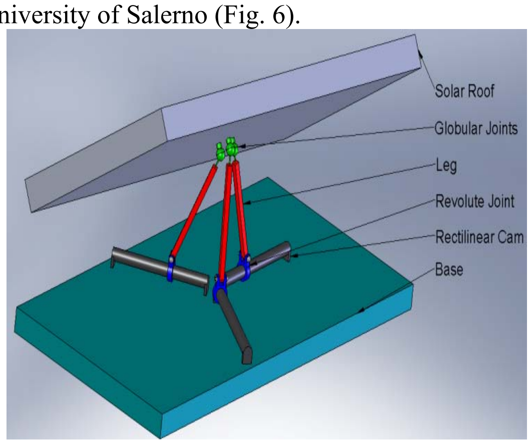

Fig. 5 - The model of moving roof realized with Solid Works

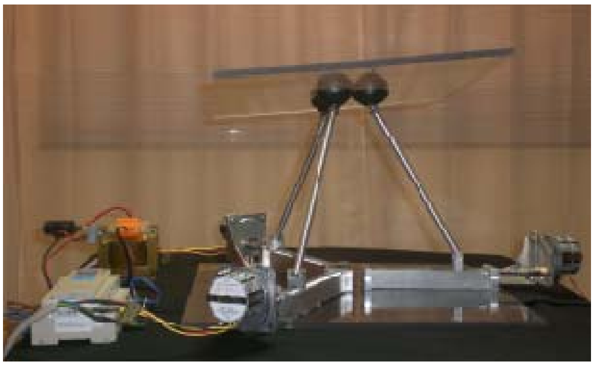

Fig. 6 - Small scale prototype of moving solar roof

A detailed analysis of the expected benefits of a moving solar roof has been performed by using hourly solar data available for different US cities [www.nrel.gov/rredc/pvwatts] [6].

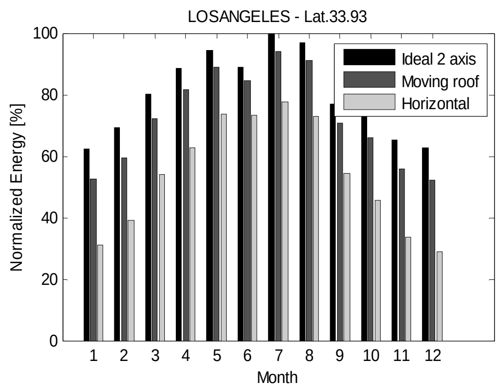

Fig. 7 – Energy collected with various options of solar roof (Los Angeles, 1988)

The database provides the measured net power for a 2-axis tracking roof and for a fixed roof at horizontal position. For each hour, the sun height is evaluated, and the average roof efficiency with respect to the ideal 2 axis roof computed by the relative efficiency curve (Fig. 8).

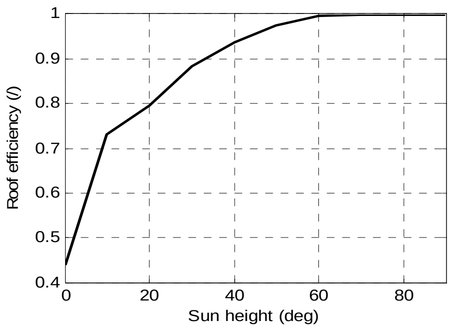

Fig. 8 – Average roof efficiency vs. sun height

The comparison of the energy collected on monthly basis in Los Angeles, normalized respect to its maximum value, is presented in Fig. 7, while an analysis on yearly basis for four different locations at various latitudes is shown in Table 1Table 1 - Yearly percent gain with respect to horizontal position for ideal two axis (A) and real mobile roof (B)

.

Location	Latitude	A	B
Honolulu	21.33	46.57	30.70
Los Angeles	33.93	48.48	34.38
Chicago	41.78	52.27	35.83
Anchorage	61.17	78.74	46.89

Table 1 - Yearly percent gain with respect to horizontal position for ideal two axis (A) and real mobile roof (B)

The results demonstrate that the proposed moving solar roof, even taking into account the kinematic constraints that do not allow perfect orientation, allows a significant gain in energy with respect to the horizontal panel, approaching the ideal 2 axis solution. The gain with respect to horizontal position range from 30% at low latitudes up to 47% at highest ones.

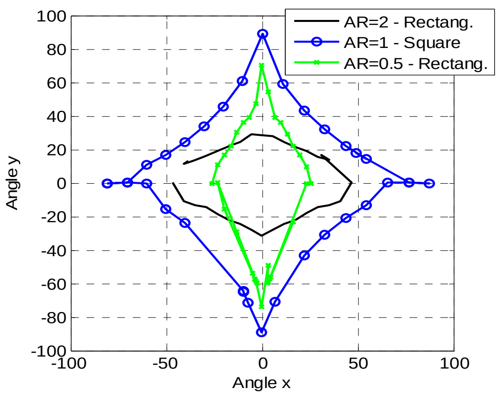

Fig. 9 – Effects of aspect ratio

It is timely to remark that these results have been obtained with a roof of rectangular shape, without bevelling, which efficiency is shown in Fig. 8. Even better results are expected by adopting an optimized geometry: in fact a systematic study has been carried out to observe the effects of the geometric variables on the performance of the roof, in terms of its capability to be oriented toward a large angular range. The study has been performed by determining numerically the limit conditions corresponding to incipient interference for various angles.

The calculation of this limit angles has been made for different geometry of the mobile roof. In terms of aspect ratio AR, defined as the ratio between roof length and width, the best results are obtained when the dimensions of the roof are equal (AR=1), while for a rectangular shape a smaller angular range can be reached (Fig. 9)

The adoption of bevelling can allow reaching a larger angular range [6] because the interference with the vehicle occur in correspondence of the roof vertices. Anyway, it should to be considered that bevelling also reduces the net area for solar panels. Therefore, these aspects have to be examined jointly.

In a previous paper [6] it has been shown that the best performance in terms of orientation capabilities are achieved when roof shape approaches to a circular one and when the distance between the globular joints (
Fig. 5) is minimized.

Finally, it has been also shown that the use of a mobile solar roof on a PV assisted vehicle is near to economic feasibility, and that can reach very interesting pay-back values in countries like Italy [6].

3. KINEMATIC MODEL

The roof geometry corresponding to a given orientation is evaluated by means of the kinematic model by solving a problem of constrained optimization:

$$min_x f(x) \qquad (2)$$

subject to the constraints:

$$G_i(x) \leq 0 \qquad (3)$$

$$E_i(x) = 0 \qquad (4)$$

The six decision variables x are represented by the three sliding s_i of rectilinear cam and the three angles α_i between the axes of actuations and their prismatic joint. The objective function f(x) to be minimized is the angle of incidence between the sun ray and the normal to the roof plane. The equality constraints E(x) express the condition that the computed values of the three legs are equal to the assigned value. The inequality constraints G(x) express the condition of no interference between i) the solar roof and the vehicle (i.e. the quote z should be greater than zero for all the points), and ii) between the legs and the solar roof. When the constraints are satisfied, the roof can be oriented exactly toward the sun, otherwise is would be oriented in the "best" way, to maximize the direct component of solar energy. The problem is solved by means of classical 2nd order optimization algorithms. The position of the roof with respect to the vehicle can be characterized by the angles between the roof plane and the axes β_x and β_y, oriented toward vehicle width and length respectively. The angles corresponding to sun position at different sun height and for various orientations of the vehicle (relative azimuth of vehicle respect to sun) can be also computed [6].

According to the roof kinematics and the involved mechanisms, the contact along the screw/nut surfaces in relative motion is also analysed by means of forces projection on a sloped plane with respect to the screw axis. The evaluation of the mechanical work spent is integrated in to the roof model, to estimate the time required to restore the energy spent based on actual conditions [6]. This feature is used within the model based control depicted in the following paragraph, in order to decide if the roof should be actuated or not (for instance, this occurrence may result for low insulation in the late afternoon, and during night of course), and to compute the best trajectory to achieve the optimal position.

4. TOWARD A MODEL BASED CONTROL OF SOLAR ROOF

The presented models represent the basis to develop a model based control system for the moving solar roof. It has been decided to move this roof only during parking phases because, in the prevailing use of such vehicles, most of solar energy is captured during parking time. The control scheme is being implemented on a small scale prototype of solar roof (Fig. 6), actuated in LabVIEW by step motors. The solar radiation is measured by a pyranometer mounted on the moving roof. Some experimental data are presented in Fig. 10, where the ratio between the maximum energy captured by the roof and the energy measured at horizontal position is compared with the theoretical value of such ratio, computed by eq. (1), considering sun position.

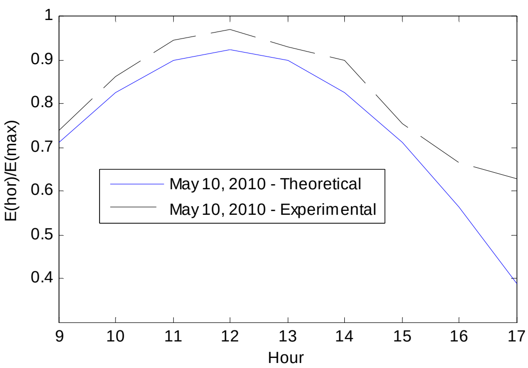

Fig. 10– Energy fraction at horizontal position. Theoretical vs experimental values (Fisciano, May 2010).

It can be observed that, although the trends are similar, some significant differences can occur, particularly at lower sun height (late afternoon). The differences are due to the fact that, besides direct radiation, diffuse and reflected components may also be present; moreover, kinematic constraints may prevent from reaching optimal orientation at lower sun height.

4.1 Control system scheme

The flow chart of control system structure, including both feed-forward and feedback control, is shown in Fig. 11. A GPS module provides vehicle position (latitude φ, longitude L) and orientation (azimuth), and also actual date and time. The sun position (declination δ, hour angle h, height ϑ_s, azimuth Φ_s) is computed by the following relationships [7]:

$$\delta = -23.45 \cdot \cos\left(\frac{2\pi(N+10)}{365}\right) \quad (5)$$

$$h = -180 + 360\frac{hour}{24} \quad (6)$$

$$\vartheta_s = arcsin(cos(h)\cos(\delta)\cos(\varphi) + \sin(\delta)\sin(\varphi)) \quad (7)$$

$$\Phi_s = \sin^{-1}\frac{\cos\delta\sin h}{\cos\vartheta_s} \quad (8)$$

The optimal roof angles (β_x, β_y) that maximize direct solar energy are then evaluated, from the relative azimuth $\Phi_s - \Phi_v$:

$$A_1 = \cos(\vartheta_s)\cdot\sin(\Phi_s - \Phi_v) \quad (9)$$

$$B_1 = \cos(\vartheta_s)\cdot\cos(\Phi_s - \Phi_v) \quad (10)$$

$$C_1 = \sin(\vartheta_s) \quad (11)$$

$$\beta_{x,opt} = arctg\left(-\frac{A_1}{C_1}\right) \quad (12)$$

$$\beta_{y,opt} = arctg\left(-\frac{B_1}{C_1}\right) \quad (13)$$

But, as discussed before, in real cases the position that maximizes net solar power could be different from the theoretical one, due to: i) presence of diffuse and reflected radiation, due to clouds and buildings; ii) presence of shadow, preventing direct view of the sun.

The best position can be of course found by processing the power data provided by PV panels, adopting for instance a Perturb&Observe approach. Of course, a suitable Maximum Power Point Tracking (MPPT) should be adopted, to maximize power extraction at each roof position [9].

But, since the PV panel provides a single maximum power data for a given roof position, it would be necessary to move the roof to perform such search. This method may lead to inefficient search, and therefore to unnecessary energy consumption, in case that the relationship between position and power is complex, due to presence of clouds and obstacles.

In order to overcome these problems, it is proposed to combine the use of GPS data and of PV power data with use of a webcam, to detect the position of the sun. More in general, it should be decided if the solar roof has to be moved or not (for instance, this occurrence may result for low insulation in the late afternoon, and during night of course). The energy to be spent to move the roof is therefore estimated as a function of starting and final position, as shown in a previous paper [6]. Based on the estimate of maximum power achievable, the minimum parking time to obtain a positive gain in net energy is then computed.

If the minimum parking time is lower than the expected duration of parking phase, the tracking system is actuated. In this case, the roof angular position corresponding to maximum solar power is computed by the equations (14)-(18), and the relative positions of the slides are computed by a Matlab module. Finally, the number of pulses for the step motors are computed and actuated by a LabVIEW module. When the target condition is reached, the process is repeated, to check if optimal position has been achieved.

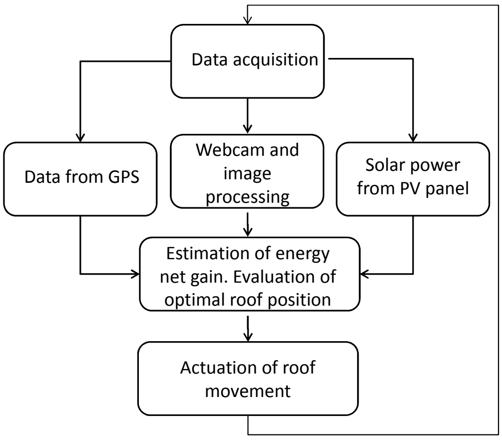

Fig. 11- Structure of solar roof control system

4.2 The control through the use of a webcam

The digital camera (or webcam) is mounted in the center of the solar mobile roof, and takes a picture of the sky. The image data are processed by an algorithm in Matlab, in order to compute the position of the sun and to estimate weather conditions.

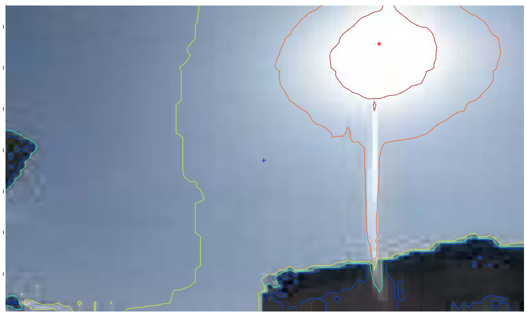

Fig. 12 - Picture of the sky: sunny conditions.

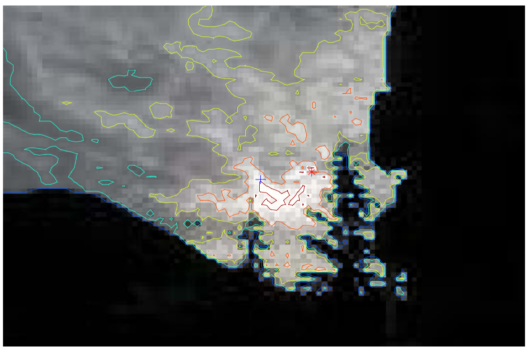

Fig. 13 - Picture of the sky: cloudy conditions.

Typical pictures with sunny and cloudy conditions are shown in Fig. 12 and Fig. 13. The red symbol * (point R) indicates the center of mass of the points corresponding to maximum brightness and the blue symbol + (point B) indicates the center of the picture. Some iso-level curves of brightness are also plotted.

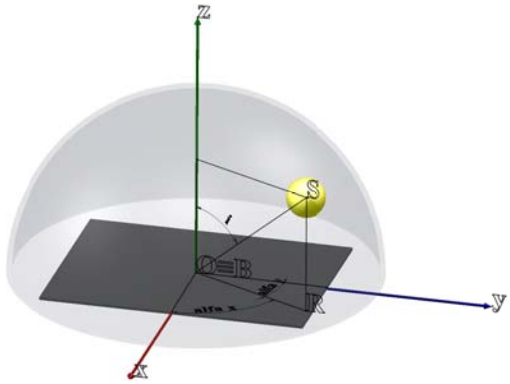

Fig. 14- Representation of solar roof and sun position.

In Fig. 14, the gray plane coincides with the plane of the camera, fixed to the solar roof. The angle of incidence *i* and the points B (center of the image) and R (maximum brightness), shown in Fig. 12 and Fig. 13, are also represented. The goal of the roof control is that the red and blue points (Fig. 12 -Fig. 13) must overlap, so that the direction of the normal coincides with the direction of the maximum brightness, and the solar power is maximized. The movement control can be achieved starting from the following geometric relationships:

(14)

(15)

(16)

(17)

(18)

where x and y are the coordinates of R, *i* is the angle of incidence, and β_x and β_y are the optimal values of the normal of the roof.

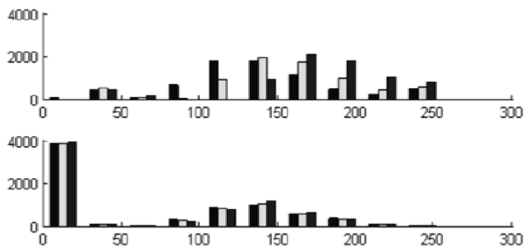

Fig. 15. Brightness distribution (0-255) for Red, Green and Blue colours, in sunny (upper) and cloudy (lower) conditions.

By processing image data, it is also possible to analyze sky conditions, in order to distinguish between sunny and cloudy weather, also to decide if solar roof should be moved or not. To this end, the distribution of brightness in the three basic colours (RGB) has been analyzed (Fig. 15). It can be observed that in sunny conditions there is a higher number of pixels with high brightness, particularly for the blue colour (3^{rd} bar), while in case of cloudy conditions most of pixels have lower brightness values.

The pictures shown in Fig. 12 and Fig. 13 have been taken by a digital camera at high resolution and then reduced to low resolution (100x75 pixels), in order to reduce computational time. This resolution, compatible with low cost webcams, seems sufficient to extract useful information from the pictures, while computational time needed for image processing is less than 0.5 s, compatible with the exigencies of real-time control. Further studies have to be done to choose a webcam of adequate optical properties, compatible with outdoor use, and of limited cost.

5. CONCLUSIONS

The use of a mobile solar roof for parking phases can give a relevant contribution to enhance solar power, for a PV assisted vehicle. The contribution is particularly significant at high latitudes, so extending the potential market of solar assisted vehicles. A proper choice of roof geometry and dimensions can be achieved by optimal design approach, allowing to maximize solar power in most of cases.

In order to enhance the benefits of a moving solar roof, the energy consumption related to its movement should be minimized, and unnecessary movements avoided. To this end, a control procedure based on combined use of the solar power data provided by the PV panel, on information derived by a GPS module and by processing the sky images taken by a webcam has been presented. The control system is currently being implemented on a small scale prototype.

REFERENCES

[1] Letendre S., Perez R., Herig C. (2003), Vehicle Integrated PV: A Clean and Secure Fuel for Hybrid Electric Vehicles, *Proc. of the American Solar Energy Society Solar 2003 Conference*, June 21-23, 2003, Austin,TX.

[2] Rizzo G. (2010), Automotive Applications of Solar Energy, 6th IFAC Symposium "Advances in Automotive Control", Munich, July 11-14, 2010.

[3] Adinolfi G., Arsie I., Di Martino R., Giustiniani A., Petrone G., Rizzo G., Sorrentino M. (2008) “A Prototype of Hybrid Solar Vehicle: Simulations and On-Board Measurements”, Proc. AVEC 2008, Oct.6-9, 2008, Kobe (Japan) 917-922 Soc.of Automotive Engineers of Japan - ISBN: 978-4-904056-21-9.

[4] Arsie I., Rizzo G., Sorrentino M. (2007) Optimal Design and Dynamic Simulation of a Hybrid Solar Vehicle, *SAE TRANSACTIONS - JOURNAL OF ENGINES* 115-3: 805-811

[5] Arsie I., Rizzo G., Sorrentino M. (2008, I) A Model for the Optimal Design of a Hybrid Solar Vehicle *Review of Automotive Engineering*. Society of Automotive Engineers of Japan (JSAE) 29: 3. 439-447

[6] Coraggio G., Pisanti C. Rizzo G., Senatore A. (2010), A Moving Solar Roof for a Hybrid Solar Vehicle, 6th IFAC Symposium "Advances in Automotive Control", Munich, 12-14 July, 2010.

[7] Quaschning V. (2003), "Technology fundamentals - The sun as an energy resource". Renewable Energy World 6 (5): 90–93.

[8] Tsai L. W. (1999), Robot Analysis: the mechanics of serial and parallel manipulators, John Wiley & Sons, Inc., USA.

[9] Femia N., Lisi G., Petrone G., Spagnuolo G., Vitelli M. (2008), “Analysis of Photovoltaic Systems with Distributed Maximum Power Point Tracking”, Proc. of IEEE International Symposium on Industrial Electronics ISIE08, June 30-July 2 2008 pp. 2408 - 2413.