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Design and energetic evaluation of a mobile photovoltaic roof for cars

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Abstract

Hybrid electric vehicles, associated with photovoltaic panels, are gaining interest mainly for two reasons: the increasing attention on the recourse of green transports and the production of electricity by a gratis and largely diffused source of energy, the solar one. Previously a considerable gain of solar energy for tracking system instead of fixed horizontal photovoltaic ones has been demonstrated and validated by historical data taken from an online calculator PvWATTS. Otherwise, there is a difference between solar tracking systems for fixed pants and for mobile applications. In this paper a prototype of a tracking solar system for vehicles and the energetic analysis has been presented. After the presentation of the system adopted, geometric optimization, it has been presented the energy evaluation: there is the computation between energy solar gain, mechanical energy spent to move the roof and energy losses, computed with a MATLAB® tool named SimMechanics™.

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Key words: solar energy, tracking system, parallel robot, photovoltaic panels, hybrid vehicles.

1. Introduction

Nowadays a great attention is given to renewable energy especially due to fossil fuel depletion and their increasing costs, environmental pollution and global warming issues. Renewable energies could offer a clean and viable solution to meet our planet's growing environmental and energy challenges.

Solar radiation is an important natural energy source because renewable, free and largely diffused. The Sun provides the Earth with an enormous amount of energy.

The potential of solar energy, to produce heat and electricity to supply our modern economies in a variety of productive activities, has been widely demonstrated but not yet widely adopted around the globe due to relatively cheap fossil fuels [1].

Among energy technologies, photovoltaic (PV) systems have experienced the highest growth rate in the world (60% in the period from 2007 to 2012).

Green mobility is gaining an increasing importance: lots prototypes of electric, hybrid vehicles have been developed. But also attention on the integration of photovoltaic panels in road vehicles, to produce electricity, has been given due to many reasons [2][3]: i) the degree of electrification is expected to grow significantly in next years in terms of fleet distribution [1][4] ii) considerable improvement in solar panel efficiency has being attained, and iii) significant reduction in their costs has been achieved, due to their fast increasing diffusion [5].

Important car companies are interested in Hybrid Solar Vehicles (HSV) particularly Toyota with Toyota Solar Prius, Ford with its last prototype of C-MAX Solar Energi. Even at University of Salerno, during two important projects, two prototypes of HSV have been developed by transforming traditional vehicles into an HSV: a Porter Glass Van during Leonardo Project [6] and a Fiat Grande Punto during Hy Solar Kit project [7]. With this last prototype the main aim is to transform aftermarket a traditional vehicle into an HSV with the use of a kit.

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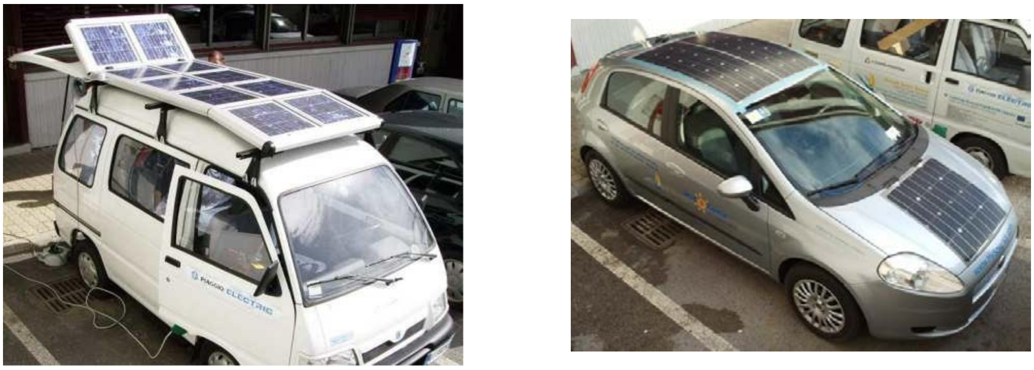


Fig. 1. Two different prototypes of HSV at University of Salerno

To gain a greater amount of solar energy, it is necessary that the angle of incidence is zero.

A possible solution is the one adopted by FORD: the C-MAX Solar Energi uses a plug-in hybrid system; into a unique canopy, that was designed at Georgia Tech, according to a Ford press release, there are Fresnel lens that Ford says boosts the impact of the sun's rays by a factor of eight. The car itself can autonomously reposition itself throughout the day to take advantage of the sun's position as it makes its trek across the sky [8].

Fig. 2. C-MAX Solar Energi, plug in hybrid electric vehicle.

The importance of a greater gain of solar energy has been considered also at University of Salerno. An aftermarket solution could be the adoption of a self orienting photovoltaic roof for vehicles. There are some specific aspects that make the study of a moving roof on a car different from a fixed plant:

- car orientation during parking is not fixed;
- solar exposure could be worse than in fixed plant;
- actuation must be faster than in a fixed plant;
- parking time may be not known;
- aerodynamic losses and additional weight should be minimized;
- perfect orientation could not be achieved in all conditions due to possible kinematic constraints.

The decision of when to move the solar roof is very important: it is suggested to use it only during parking phases because i) the use of this tracking roof during driving would result in car instability, aerodynamic losses, and excessive energy losses for orienting the panel, if car orientation is rapidly varying and ii) hybrid solar cars maximize their benefits when car is used no more than 1-2 hours per day, as it happens for a large number of users. Therefore, most of the solar energy is taken during parking.

The model of a prototype of a self orienting solar system applied to road vehicles, its geometric optimization of the overall space and the energy evaluation will be presented in this paper. The energetic convenience has been underlined, evaluating the recovery time: after the computation of the solar energy gain, it has been calculated also the mechanical energy. In this last case energy losses due to friction has been computed through a Matlab tool, SimMechanics.

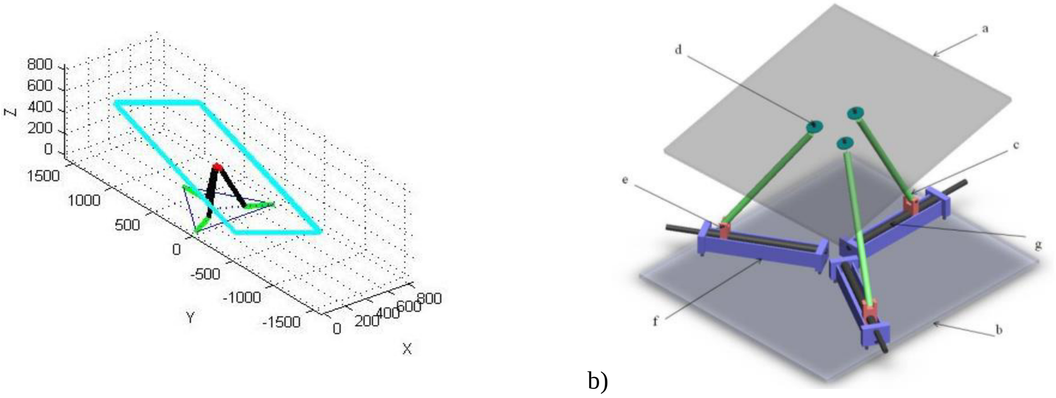
2. System setup

2.1 The solar roof prototype model

To have a greater gain of solar energy for vehicles transformed aftermarket into an HSV, a tracking system has been mounted on the roof of an hybrid vehicle.

The roof has been though as a parallel robot with three degrees of freedom [9]. For the physical realization of the prototype firstly a mathematical model has been developed through a Matlab algorithm as explained in a previous work [10].

The main elements of the prototype have been mathematically shown in Matlab (see Fig. 3. a)) and then modeled in Solid WORKS (see Fig. 3. b)).



a) b)

Fig. 3. a) Graphical output by the MATLAB model, b) Mobile solar roof prototype 3D modeled

Table 1 - Main components of the mobile system

Solar roof components
Solar roof, mobile platform
Base, fixed platform
Leg
Globular joint
Sliding
Track
Endless screw

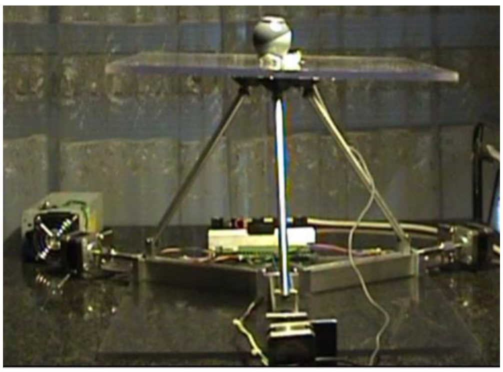


Fig. 4. Mobile solar roof prototype, moved by three step motors connected to a NI schedule and a webcam mounted in the middle of the roof

A prototype has been realized in the laboratory to validate each result (see Fig. 4). The control system for the mobile roof has been implemented in LabVIEW; the webcam mounted in the middle of the roof is necessary for the control strategy [10].

The roof geometry is evaluated by means of the kinematic model shown in [10], by solving an optimization problem:

$$\min_x f(x) \quad (1)$$

$$G_i(x) \leq 0 \quad (2)$$

$$E_i(x) = 0 \quad (3)$$

- The six decision variables x are represented by the three sliding s_i of rectilinear cam;
- 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;
- The equality constraints E(x) express the condition that the computed values of the three legs $l_{ci,j}$ are equal to the assigned value l;
- 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 (2)(3) are satisfied, the roof can be oriented exactly toward the sun, otherwise it would be oriented in the "best" way, to maximize the direct component of solar energy.

To know how to orient the mobile roof is necessary to compute solar angles [10][11]. The problem (1)-(3) is solved by means of classical 2nd order optimization algorithms (Augmented Lagrangian approach combined with Quasi-Newton algorithm), implemented in the optimization tool of MATLAB. Computational time is order of few seconds, on a Sony VAIO PC. In Fig. 5 it is shown that at highest sun eight roof angle range must be greater.

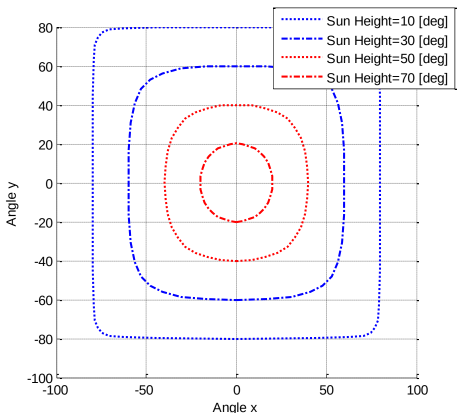


Fig. 5. Roof angles at different sun height

2.2 *Minimization of the overall dimension at rest position*

In previous works roof geometry has been optimized, in terms of the largest angular range obtained: the maximum angular range is reached when roof geometry is close to circular shape.

Despite of this optimization, the model is not yet marketable because at rest position the overall dimensions are too high, and this is the main cause for aerodynamic losses. So it has been conducted another analysis considering the main forces acting on it: the weight force (P) and the wind pressure (V). These cause compression and bending stresses.

Table 2 - Main data used during the optimization

Characteristic	Value
Roof length [m]	1.46

Roof width [m]	1
Mean wind speed in Italy [m/s]	5
Material of the mobile roof	Polycarbonate flexan
Density of polycarbonate flexan [kg/m^3]	1200
Solar panels	Monocrystalline ENECOM

It is possible to reduce overall dimensions, if at start position legs are horizontal. Each leg can be seen as a fixed-end beam loaded at the other end (see Fig. 6).

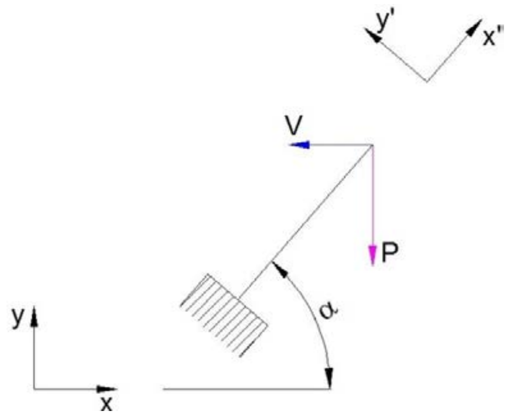


Fig. 6. 2D scheme of a loaded leg

The sizing has been done considering the most critical condition: each force acts totally on each leg, when α angle is the biggest one obtainable (almost 90°) wind pressure effect is the most critical one.

It is possible to compute wind pressure through Bernoulli's theorem considering wind speed (Fig. 7), shown in [12].

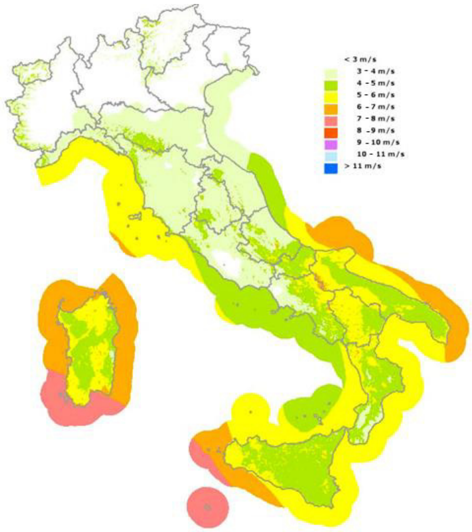


Fig. 7. Wind map in Italy

Bernoulli's theorem is applied between an undisturbed section and the surface of the panel:

$$p_1+\frac{1}{2}\cdot\rho\cdot v_1^2+\rho\cdot g\cdot h_1=p+\frac{1}{2}\cdot\rho\cdot v^2+\rho\cdot g\cdot h \quad (4)$$

The roof has been designed considering real roof dimensions of a Fiat Grande Punto: main data are presented in Table 2 and shown in Fig. 8.

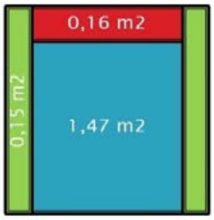


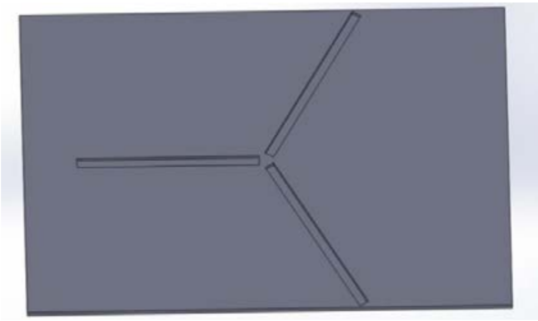
Fig. 8. Roof dimensions of a Fiat Grande Punto

The weight force is obtained summing up roof's and panels' weight.

The legs' minimum diameter is obtained considering these forces plus a security factor and their availability on the market: the diameter must be at least 4.8 mm, then it has been valuated a diameter of 6 mm.

To realize a greater optimization of these overall dimensions, some groves have been realized:

a) for the supports of the worms and for the three legs in the fixed and in the mobile plant (see Fig. 9 a));
b) for negative shape of the three globular joints in the mobile roof (see Fig. 9 b)).

a) 

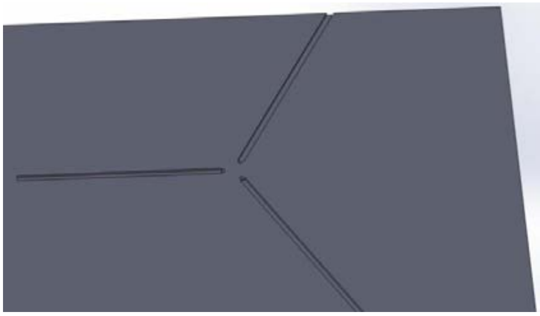
b) 

Fig. 9. a) Fixed plant with the three grooves, b) Mobile roof with the semi-spherical and the three grooves for the legs' lodging

After this optimization the model is (see Fig. 10):

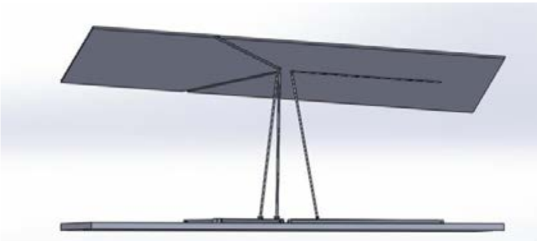


Fig. 10. 3D model after the optimization of the overall dimension

To sum up, comparing the distances, between the fixed and the mobile roof, of the model previously realized and of the model just designed is shown that the reduction is considerable, about 40 mm (see Fig. 11).

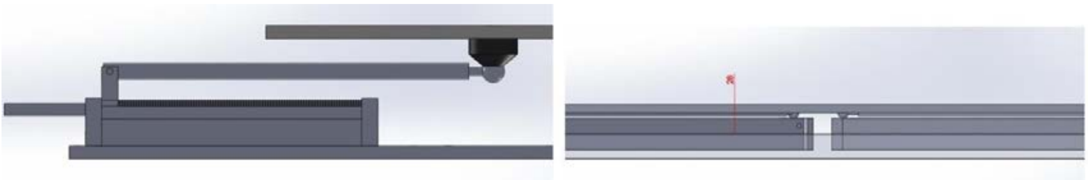


Fig. 11. Comparison of the two models at rest position

3. Energy evaluation

It has been conducted an energetic evaluation to underline the energetic convenience of the prototype.

The main kind of energies involved for this evaluation are: the solar energy gain of the mobile system vs. the fixed horizontal one, the mechanical energy necessary to move the roof, the energetic consumption of the magnet, energy losses due to friction.

3.1 Theory and calculation

3.1.1 Solar energy gain

Data from the database PvWATTS have been used to compute solar energy gain: in this database the averages of solar energy calculated in several years in different cities at different latitudes and in different period of the year are presented. The database provides the measured net power for a 2-axis tracking roof and for a fixed one at horizontal position. The comparison of the energy collected on monthly basis in Salerno, normalized respect to its maximum value, is presented in Fig. 12. The results demonstrate that the proposed moving solar roof [13][14][15](taking into account the kinematic constraints of the prototype) allows a significant gain in energy with respect to the horizontal panel. The solar energy gain is higher at high altitude respect of low latitude: a 30% gain at low latitudes up to 47% at highest ones.

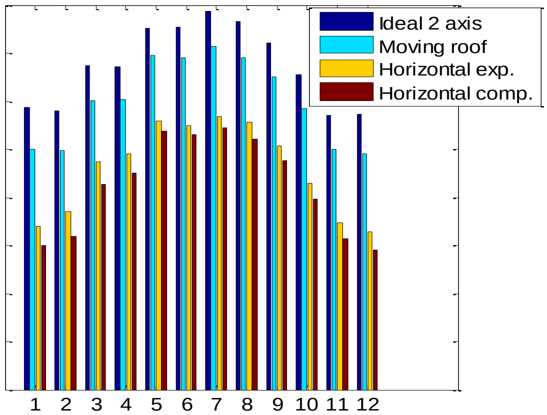


Fig. 12. Energy collected with various options of solar roof (Salerno, 2010) each month

3.1.2 Mechanical energy

According to the roof kinematics and the involved mechanisms as it has also been explained in [10], the contact along the screw/nut surfaces in relative motion may be analyzed by means of forces projection on a sloped plane with respect to the screw axis. ω is the rotational speed of the screw, M_m is the DC motor torque, r_m is the screw radius. [15][16][17]. The following calculation of the mechanical work required for a general s_1-s_2 stroke of the leg base slider may be performed:

$$E_m = L_m \cdot t \qquad (5)$$

$$L_m = \int_{\theta(s1)}^{\theta(s2)} M_m(\theta) d\theta = \int_{\theta 1}^{\theta 2} F(\theta) r_m \tan(\alpha+\varphi)\, d\theta = r_m \tan(\alpha+\varphi) \int_{\theta 1}^{\theta 2} \frac{W_L(\text{roof\_orientation})}{\cos\beta(\text{roof\_orientation})} d\theta \qquad (6)$$

It is necessary to achieve an irreversible mechanism and boundary lubrication regime between screw and nut, so the friction coefficient has been imposed φ≈α=10°:

$$\eta_m = \frac{\tan\alpha}{\tan(\alpha+\varphi)} \approx 0.48 \qquad (7)$$

The main data considered are shown in next table.

Table 3 - Main data considered to compute mechanical energy

Characteristic	Value
Motor speed [rpm]	100
Pitch [mm]	3
Roof weight [N]	173.6
Axial force [N]	200
Mechanical work [J]	460
Solar energy gain [%]	30
Solar average power [W]	200

$$E_m = E_{m0} + E_{m1}(\Delta t) + E_f \quad (8)$$

$$E_{m0} = F \cdot \Delta t \quad (9)$$

E_{m0} is the energy of the first detachment force, E_f is the energy lost for friction losses.

The characteristic of an asynchronous motor is shown in Fig. 13.

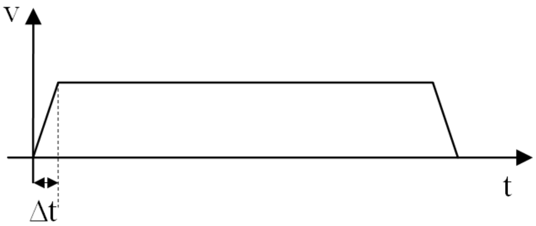


Fig. 13. Characteristic of asynchronous motor.

$$F = mg \pm ma \quad (10)$$

Considering the data in Table 3 it has been computed that the energy spent to move the roof would be restored in almost 10 s.

The evaluation of the mechanical work spent can be also integrated into the roof model, to estimate the time required to restore the energy spent based on actual conditions. A better computation of energy losses due to friction will be better explained in next paragraph.

3.1.3 Energy friction losses

The validation of the mathematical model presented has been carried out through a MATLAB / Simulink tool the SimMechanics (see Fig. 14).

Firstly parametric equations representing the system have been developed.

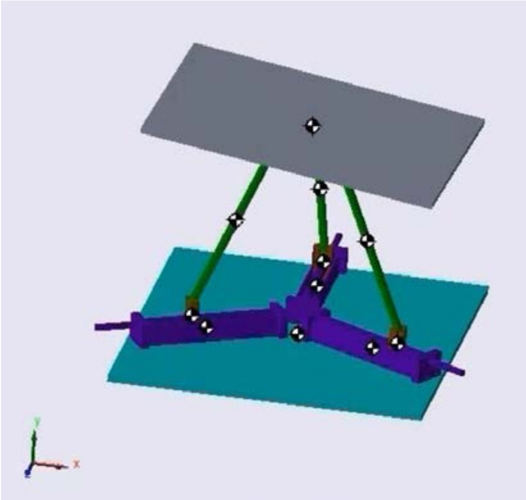


Fig. 14. Representation of a frame during the simulation of the solar roof with SimMechanics.

During simulation motion equations are solved, solutions are applied, and the final movement/orientation is presented. Differential equations are solved by ode45.

The model previously realized in SolidWorks has been used in SimMechanics and a series of mathematical evaluation has been done. All the changes realized in SolidWorks are loaded in SimMechanics: CAD systems do not guarantee the mass, while using SimMechanics, the moment of inertia could be modified.

In this work the model realized in SimMechanics is used only to evaluate friction losses.

Friction effects have been evaluated making a comparison between two scenarios, with and without friction.

For both scenarios some conditions have been considered:

- The same initial values of s;
- The same power of the three step motors applied to the sliders;
- The same final values of s;

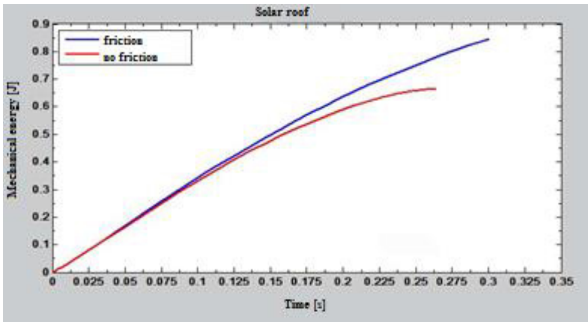


Fig. 15. Mechanical energy spent to move the roof

Obviously, to achieve the same inclination of the panel, more time (obviously more energy) has been spent in the real model with respect to the ideal one (Fig. 15).

3.1.4 Electromagnetic energy

To reduce overall dimension at rest position, legs must be horizontal. In this case the energy necessary to start the orientation tends to infinite ($E_{m0} \rightarrow \infty$).

To overcome this problem, it has been thought to install a thrust electromagnet between mobile and fixed platform of the system, in the middle: so $E_{m0} \neq 0$ because the roof is lifted of a small amount.

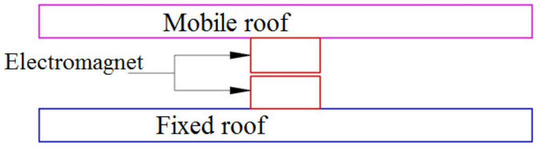


Fig. 16. Scheme of electromagnets positions

In this way it is possible to activate the electric motors for movement.

3.2 Recovery time

The energetic feasibility of this prototype is valuated through the recovery time t_r (11)[18]:

$$t_r = E_m / P_g \quad (11)$$

Knowing speed motor, it is possible to compute the acceleration: since ma<<mg it is possible to consider the system almost static. For a small Δt also the force connected to friction losses is almost equal to the ideal case.

An example of the recovery time computed in Salerno during a day is:

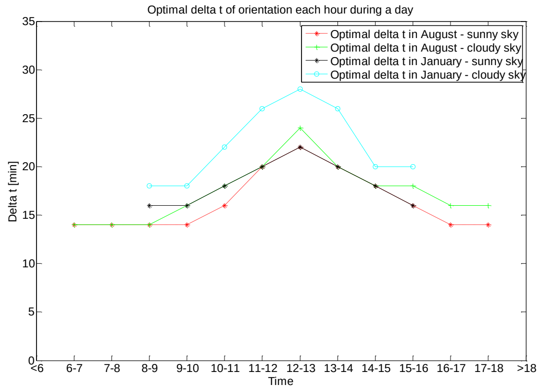


Figure 1 - Recovery time measured in Salerno at different conditions

There is a real energetic advantage if t_r<<t_p, where t_p is the parking time: in case of hybrid vehicle, where there is a considerable advantage if the car is driven only few hours a day so almost 8 hours the car is parked and the solar energy is caught. Considering data shown in this figure it is possible to say that in terms of recovery time is always convenient the solar mobile roof.[19][20]

4. Conclusions

Nowadays the use of green energy also for transport is gaining great importance. To gain more solar energy a solution could be the adoption aftermarket of a mobile solar roof. This system has been thought as a parallel robot with three degrees of freedom. Its geometry has been optimized firstly in MATLAB: the geometry with whom it is possible to gain the larger angular range is circular.

The main problem is the overall dimensions at rest position; they are the main causes of aerodynamic losses. In this work it is presented how these overall dimensions have been reduced, through the optimization of the elements of the solar roof considering the main forces acting on it: wind and weight force.

There is the computation of the energy convenience of the solar roof: in this computation also friction losses have been evaluated.

The energetic convenience has been underlined by the calculation of the recovery time: the recovery time is negligible respect of the parking time. And the delta time between two different orientation is different during the day, at different seasons and at different latitudes.

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