Multi-objective Optimization of a Mechatronic Solar Tracking Mechanisms

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***Abstract*—In this work, the multi-objective optimization of a dual-axis solar tracker is carried out by using a virtual prototyping software platform that integrates CAD (Computer Aided Design) – CATIA, MBS (Multi-Body Systems) – ADAMS and DFC (Design for Control) – EASY5 computer aided engineering programs. The solar tracking mechanism performs the bi-axial orientation of a PV panel, with the purpose to increase of the amount of incident solar radiation captured by the conversion system, thus improving its energy output. The optimization study aims to determine the optimal arrangement of the linear actuators that control the two degrees of freedom of the system (i.e. the diurnal and elevation movements of the PV panel) and the optimal tuning of their control elements (controllers), so that to minimize the energy consumption for performing the tracking and the tracking errors (relative to the imposed orientation program), while complying with the functional and constructive requirements/constraints coming from the type of actuator used in the application (which is a real/existing one). The tracking mechanism is approached/designed in mechatronic concept (i.e. concurrent engineering), by integrating the mechanical and control subsystems at the virtual prototype level.**

***Index Terms*—PV panel, solar tracking mechanism, optimization, mechatronic system, virtual prototyping.**

I. Introduction

Research in the field of renewable energy systems is a global priority because they offer viable alternatives to a series of major problems that humanity is facing, such as the limiting and polluting character of fossil fuels, global warming or the greenhouse effect. Solar energy is the most important source of renewable energy and it can be transformed into electricity or heat. The conversion method of solar radiation in electricity is well known - the photovoltaic (PV) effect.

Solar radiation is the main entry point in designing PV systems. The amount of solar radiation is not evenly distributed, varying in intensity from one geographical location to another (depending on latitude, season and time of day). The solar radiation's degree of capture can be maximized through the utilization of PV module tracking systems, which can generate an increase of the conversion system's efficiency by 20-50% relative to the fixed (without tracking) reference system [1]–[5].

Depending on the number of degrees of freedom (DOF), which reflects the number of independent movements (which occur under the forces action) of the PV system, there are two basic types of tracking mechanisms: mono-axis (DOF=1) and dual-axis (DOF=2) systems. From tracking efficiency point of view, which is reflected in the energy output of the PV system, dual-axis solar trackers are more effective than those with a single movement axis. On the other hand, it is obvious that mono-axis systems are less complex, and therefore less expensive (as designing & manufacturing cost, and subsequent maintenance) [6]–[9].

Taking into account the relative arrangement of the two movements axes, dual-axis solar trackers can be classified as follows (Fig. 1): polar (a), pseudo-polar (b), azimuthal (c), and pseudo-azimuthal (d) systems. The schematic models in Fig. 1 (where "d" represents the diurnal motion, "e" - the elevation motion, and "p" - the polar axis) are represented in the vertical plane that has as normal the East-West axis.

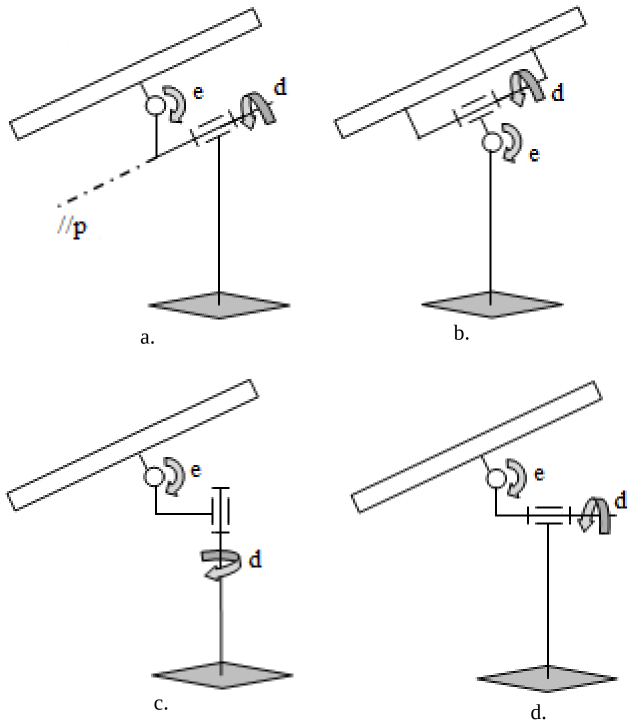

Fig. 1. Dual-axis tracking mechanisms.

As can be seen, in the polar, azimuthal and pseudo-azimuthal systems, the diurnal movement axis is the primary (fixed) axis, while in pseudo-polar systems the primary axis corresponds to the elevation movement. Each of these solutions has advantages and disadvantages (from a functional and constructive point of view), the choice of a certain type being made depending on the location where the system to be implemented and the structure to be oriented (individual/stand-alone PV panel, platform, string, or platform of strings) [10]–[13].

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According to operating principle (i.e. working mode), tracking systems can be passive or active. Passive systems working is based on the thermal expansion of a heat-sensitive fluid through some tubes arranged on the panel frame [14]. Active solar trackers are in fact mechatronic systems, in which the actuation (on one axis, or on two axes, as the case may be) is performed by using controlled motor sources (linear and/or rotary actuators). Supplementary, various types of mechanisms (linkages, gears, chain, belt and/or wire transmissions) can be found in the active systems, with the purpose to amplify the stroke of the actuating element or to avoid the occurrence of the system self-locking phenomenon (by keeping the transmission angle or its complement, the pressure angle, within permissible limits), especially if the motor sources are linear actuators.

In the active solar trackers whose source motors are linear actuators, which are cheaper than rotary actuators but can raise problems like the ones reported above, the arrangement / disposing of the actuators can also have an effect on the energy efficiency of the tracking system, through the necessary driving forces that are found in the energy consumed to achieve the sun tracking.

The application in this work is carried out for an active dual-axis pseudo-polar solar tracker, where linear actuators are used to control the two degrees of freedom (corresponding to the diurnal and elevation movements) of the PV system. The study deals with the optimal design of the tracking mechanism, the optimization goal being to improve the energetic efficiency of the PV system by minimizing the motor forces developed by actuators (thus the energy consumed for ensuring the dual-axis tracking) and the tracking errors (thus improving the tracking accuracy relative to the imposed tracking program, which is defined by the time-history variations of the diurnal and elevation angles of the PV panel). The first design objective is mainly related to the mechanical subsystem of the solar tracker (in terms of determining the optimal arrangement of the two linear actuators), while the second objective is to be achieved in the control subsystem through the optimal design of the controllers.

The optimization process is carried out by simultaneously considering the two specific subsystems (mechanical & control), which are integrated at the level of the virtual prototype, in mechatronic concept. The virtual prototyping platform used in conducting the modeling, simulation and optimization study includes CAD (Computer Aided Design) – CATIA, MBS (Multi-Body Systems) – ADAMS and DFC (Design for Control) – EASY5 computer aided engineering programs.

II. The Virtual Prototype of the Dual-Axis Sun Tracking System

As mentioned, for this work an active dual-axis pseudo-polar sun tracking mechanism was approached/ designed. The 3D model of the tracking mechanism was conceived based on the schematic model shown in Figure 1,b by using the CAD program CATIA. Subsequently, the solid model was transferred using the STEP file format to the MBS program ADAMS, where the dynamic model of the tracking system was finalized by modeling the connections between the bodies (i.e. joints), the force generating elements, and the input & output control plants.

The MBS model of the dual-axis solar tracker is shown in Fig. 2. The model includes the fixed part/sustaining pole (0), the intermediate beam (1), the PV panel frame (2), and the pistons (3/4) & cylinders (5/6) of the linear actuators. The elevation movement, whose axis is the primary / fixed one, is carried out by rotating the assembly consisting of the intermediate beam and the panel relative to the sustaining pole, through the revolute joint B. The diurnal movement occurs by rotating the panel relative to the intermediate beam, around the axis defined by the pair of revolute joints A-A’. The two linear actuators are connected to the adjacent bodies that define the aforementioned revolute joints (support - pillar, and panel - beam, respectively). The two parts of each actuator (piston - cylinder) are connected by translational joint (C, D). The actuators’ parts are connected to the adjacent bodies by revolute joints (E and G, respectively F and H).

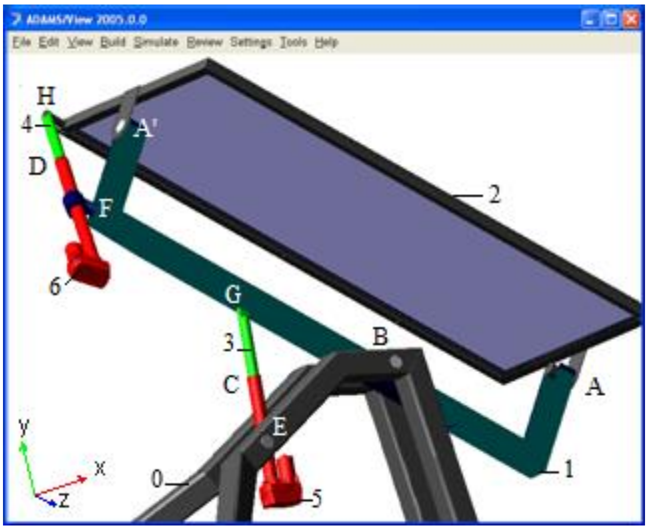

Fig. 2. The MBS model of the mechanical subsystem (ADAMS).

The motor forces act between the two parts of the actuators (cylinders - pistons), the force developed by the cylinder being applied (pull & push) to the piston along the axis of the actuator. The modeling of the actuating force is performed in accordance with the specific parameters shown in Fig. 3, where the function associated with the force is defined by means of a state variable entitled “motor_force” (which is called by the predefined function VARVAL - Variable Value), whose value is provided by the control system.

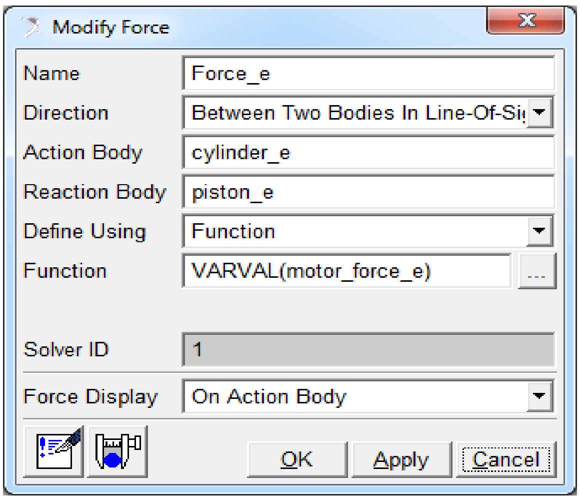

Fig. 3. The modeling of the actuating force.

The interactive communication between the mechanical and control devices is based on the input & output plants shown in Fig. 4, where IN-1 and IN-2 are the input plants /signals representing the motor forces (motor_force_e and motor_force_d, by case), while the output plants OUT-1 and OUT-2 refer to the diurnal and elevation angles of the panel, which are defined in the revolute joints A and B, by case, as the angles between the local coordinate system markers attached to the adjacent bodies.

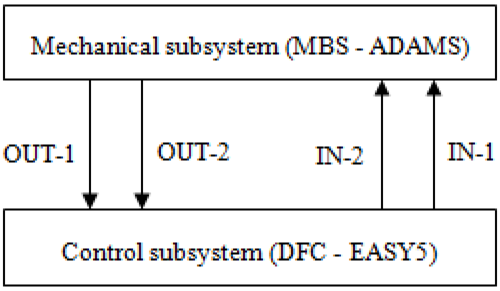

Fig. 4. The input & output plants.

The modeling of the output state variables is based on the predefined function AZ(To Marker, From Marker), where AZ stands from Angle about Z (in ADAMS, Z is considered as local movement/rotation axis). For example, Fig. 5 shows the elevation angle modeling, where the two coordinate system markers are attached to the sustaining pole (MARKER_0) and to the intermediate beam (MARKER_1), respectively.

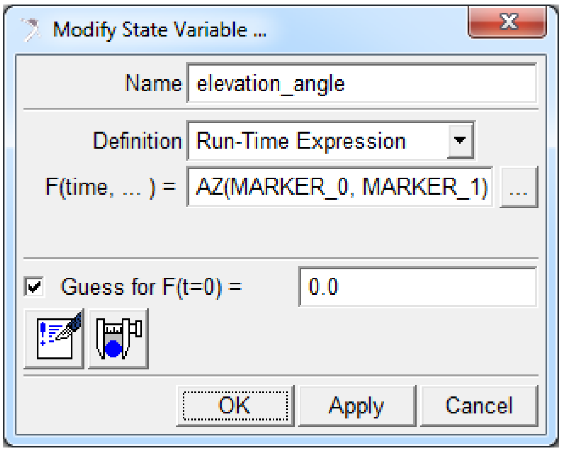

Fig. 5. The modeling of the elevation angle.

The input & output plants are transferred for the control application (EASY5 in this case) by using ADAMS/Controls, which is a plug-in for the pre-processing interface ADAMS/View. The so generated files are then imported in EASY5, where the control system is subsequently designed. In the control system block diagram, which is shown in Fig. 6, MSC.ADAMS is the interface block through which the mechanical and control models communicate (via ADAMS/Controls) by managing the input & output plants.

The current values of the diurnal (OUT-1) and elevation (OUT-2) angles, which are computed in the MBS model, are compared to the corresponding imposed angles (which define the tracking program during the day-light) by using the summing junction blocks SJ1 and SJ2, whose outputs are the tracking errors. These errors are picked up by the two PID controllers (controller_d - for the diurnal movement, and controller_e - for the elevation movement), which generate the forces necessary to be realized by the linear actuators (IN-1 and IN-2). Then, through a series of specific operations (blocks), there are determined the amounts of energy consumed for achieving the tracking along the two movement axes, which actually influence the energetic efficiency of the PV tracking system.

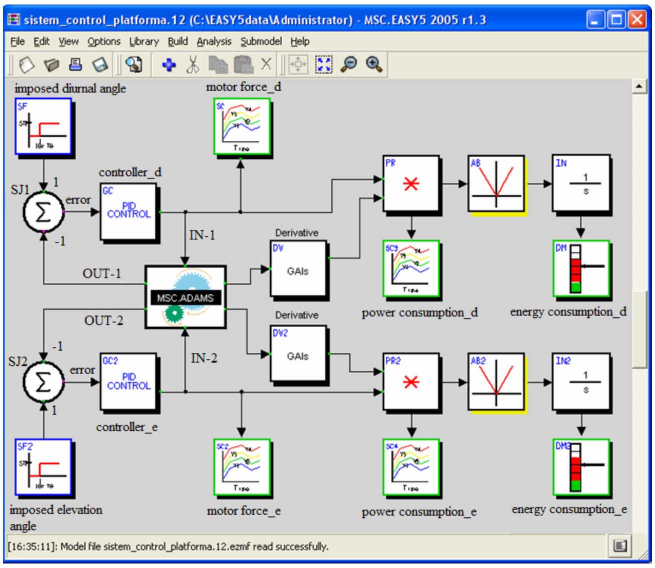

Fig. 6. The DFC model of the control subsystem (EASY5).

The optimal design of the imposed dual-axis tracking program (defined by the time-variation laws of the diurnal and elevation angles) was carried out by following an algorithm similar to that depicted in [10], the goal being to obtain an amount of incident solar radiation captured by the PV panel oriented in steps (step-by-step tracking) as close as possible to the maximum amount of radiation that could be obtained by continuous orientation throughout the day. In practice, step-by-step tracking is frequently used, given that continuous orientation, although it would ensure better efficiency, raises certain issues that make it difficult to implement [10], [13].

For the study presented in this paper (and the results shown in the forth section), the tracking program corresponding to a representative day of the year was considered, namely the summer solstice (June, 21), which is the longest daylight of the year in the Northern Hemisphere.

III. The Optimization of the Tracking System

As mentioned, the purpose of the optimization study is to improve the energetic efficiency of the PV tracking system from two points of view (which are transposed as design objectives for optimization): minimizing the motor forces developed by actuators (thus the energy consumed for achieving the dual-axis tracking); minimizing the tracking errors (thus improving the tracking accuracy relative to the imposed tracking program, which is reflected in a high degree of capture of the incident solar radiation). In the control system block diagram shown in Fig. 7, the motor forces are the inputs in the ADAMS interface block (IN-1 and IN-2), which come from the two PID controllers, while the tracking errors are the outputs from the summing junction blocks (SJ1 and SJ2).

The first design objective involves determining the optimal arrangement of the two linear actuators (i.e. the optimal values of the global coordinates of the joints by which the actuators are connected to the adjacent bodies), while the second objective aims at optimal tuning the PID controllers (i.e. the optimal values of the proportional, derivative and integral factors). In these terms, the following independent design variables (DV) were defined in the optimization process (for notations, see Fig. 2):

- the global coordinates of the connection points / joints of the diurnal movement actuator: $X_F \rightarrow DV\_1$, $Y_F \rightarrow DV\_2$, $Z_F \rightarrow DV\_3$; $X_H \rightarrow DV\_4$, $Y_H \rightarrow DV\_5$, $Z_H \rightarrow DV\_6$;
- the global coordinates of the connection points / joints of the elevation movement actuator: $X_E \rightarrow DV\_7$, $Y_E \rightarrow DV\_8$; $X_G \rightarrow DV\_9$, $Y_G \rightarrow DV\_10$; it should be mentioned that the actuator for the elevation movement is arranged in the longitudinal - vertical plane (*XY*) of the system, therefore the transversal coordinates will not be considered as design variables, but will be imposed ($Z_E = Z_G$);
- the proportional, derivative and integral factors of the controller for the diurnal movement: $P_d \rightarrow DV\_11$, $I_d \rightarrow DV\_12$, $D_d \rightarrow DV\_13$;
- the proportional, derivative and integral factors of the controller for the elevation movement: $P_e \rightarrow DV\_14$, $I_e \rightarrow DV\_15$, $D_e \rightarrow DV\_16$.

Therefore, there are 16 design variables, of which 10 in the mechanical device and 6 in the control device. Each of them is modeled by a standard/nominal value and a variation domain (minimum - maximum values). Optimization consists of searching for the optimal values of the design variables, which will ensure the fulfillment of the design objectives (minimization of the motor forces / energy consumed for performing the dual-axis tracking, and minimization of the tracking errors).

In addition, in the mechanical device, there were defined several design constraints (DC), whose role is to maintain the tracking mechanism in rational functional and constructive limits. These refer to the following aspects:

- limiting the values of the transmission angles (τ) in the two motion subsystems (diurnal - AHDF, and elevation - BGCE), in order to avoid the risk of self-locking of the mechanism, which in theory occurs when the angle is τ=0° or τ=180°, but in practice, mainly due to friction, it can occur before reaching these values, reason for which the safety limits $\tau_{min/max}$=10°/170° will be considered (for example, in Fig. 7 the transmission angle in the elevation movement subsystem is defined);
- ensuring the minimum (l_{min}) and maximum (l_{max}) lengths of the two linear actuators, and implicitly their strokes, starting from the premise that two existing actuators are used (namely Servomech ATL05-RL1-C300 for the diurnal movement, and respectively Servomech ATL05-RL1-C200 for elevation, where the value next to C corresponds to the actuator stroke, in mm) [15].

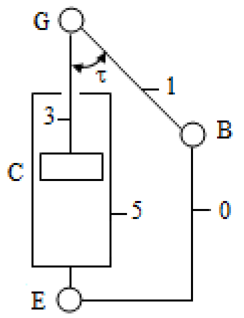

Fig. 7. The transmission angle (τ) in the elevation subsystem.

Therefore, the following design constraints (DC) were defined for the optimization process of the dual-axis tracking mechanism:

- limiting the transmission angle in the diurnal movement subsystem: $DC\_1 = \tau_{d\,min} - \tau_d$, $DC\_2 = \tau_d - \tau_{d\,max}$;
- limiting the transmission angle in the elevation movement subsystem: $DC\_3 = \tau_{e\,min} - \tau_e$, $DC\_4 = \tau_e - \tau_{e\,max}$;
- compliance with the minimum and maximum lengths of the actuator for the diurnal movement: $DC\_5 = l_{d\,min} - l_d$, $DC\_6 = l_d - l_{d\,max}$;
- compliance with the minimum and maximum lengths of the actuator for the elevation movement: $DC\_7 = l_{e\,min} - l_e$, $DC\_8 = l_e - l_{e\,max}$.

The expressions of the design constraints were defined/ modeled by considering the sign convention in ADAMS, according to which the value of the design constraint must be negative (or null at the limit) throughout the simulation, otherwise (if the value is positive) the constraint is considered to be violated. Thus, out of the multitude of variants that are obtained by combining the 10 design variables from the mechanical device (namely, DV_1 – DV_10), only those are retained that ensure the observance of the design constraints.

The effective optimization of the dual-axis tracking system was performed through one of the algorithms integrated in ADAMS, namely OPTDES-SQP (Sequential Quadratic Programming) with Centered differencing technique, which perturbs each design variable in the negative direction from the nominal value, then again in the positive direction using finite differencing between the perturbed results to compute the gradient [16].

IV. Results and Conclusions

For this work, the computations/simulations in virtual prototyping environment were carried out by considering the specific data corresponding to the summer solstice day (sunrise - 5.466, sunset - 21.183, in local time), for the Brașov geographical area (45.657974 N, 25.601198 E). The time-history variations for the diurnal (β*) and elevation (γ*) angles of the PV panel (which define the imposed dual-axis tracking program) are those shown in Figure 8 (where "d" - diurnal, and "e" - elevation). As mentioned in the second section of the paper, the tracking laws were determined based on the optimal design algorithm presented in [10]. For the diurnal movement, the return travel of the PV system to the initial position is also considered (the return is performed after sunset, in the opposite direction of the active travel, with continuous movement).

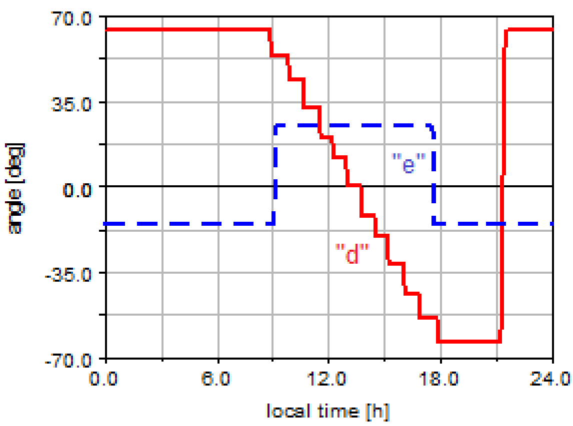

Fig. 8. The dual-axis tracking program.

The dual-axis tracking program is defined by the following numerical values: $\beta^* \in [64°, -64°]$; $\gamma^* = [-15°, 25°]$; actuating timetable for the diurnal movement: 8.839 ($\Delta\beta^*$=10°); 9.819 ($\Delta\beta^*$=10°); 10.619 ($\Delta\beta^*$=12°); 11.489 ($\Delta\beta^*$=12°); 12.189 ($\Delta\beta^*$=8°); 12.919 ($\Delta\beta^*$=12°); 13.719 ($\Delta\beta^*$=12°); 14.449 ($\Delta\beta^*$=8°); 15.149 ($\Delta\beta^*$=12°); 16.019 ($\Delta\beta^*$=12°); 16.819 ($\Delta\beta^*$=10°); 17.799 ($\Delta\beta^*$=10°); actuating timetable for the elevation movement: 9.069 ($\Delta\gamma^*$=40°), 17.569 ($\Delta\gamma^*$=-40°); return to starting/initial position: 21.183 ($\Delta\beta^*$=-128°). In those presented above, $\Delta\beta^*$ / $\Delta\gamma^*$ is the size of the tracking step for the diurnal / elevation movement.

It was considered (as a sign convention) that the diurnal angle is positive in the morning and negative in the afternoon, the reference position (β^*=0°) being the noon one, in which the PV panel faces South. The elevation angle is positive when the PV panel is facing South, respectively negative when facing North, the reference position (γ^*=0°) being the one in which the panel is arranged horizontally.

With the above described dual-axis tracking program, by applying the computation algorithm presented in [10] (which is based on the Meliss empirical model [17]), the amount of incident solar radiation that is normal on the PV panel surface was obtained, as shown in Fig. 9 (curve "I"). The high effeciency of the tracling program is proven by the fact that the incident radiation curve is very close to that corresponding to direct radiation (curve "D"), which would be obtained by the continuous orientation of the panel throughout the day-light.

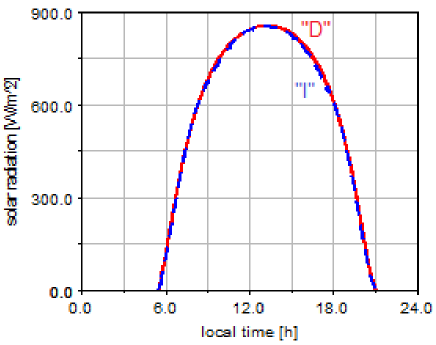

Fig. 9. The incident and direct solar radiation.

By applying the optimization algorithm depicted in the previous section of the work, the optimal configuration of the tracking system (from the mechanical and control devices point of view) was obtained. In this configuration, the linear displacements in the two actuators corresponding to the imposed tracking program of the PV panel are those shown in Fig. 10. As can be seen, the linear displacements in the two actuators follow without problems the maximum possible strokes, which are imposed by the type of actuator (ATL05-RL1-C300 / C200).

It should be mentioned that the diurnal movement actuator is fully compressed when the PV panel is facing East (β^*=90°), while in the case of the elevator movement actuator the compressed position is that in which the panel is tilted to the North with the initial elevation angle from the longest day of the year, i.e. the summer solstice day (γ^*=-15°).

The proper functioning of the tracking mechanism is also demonstrated by the variations of the transmission angles (Fig. 11), which are permanently kept within acceptable limits, so that there is not the slightest risk of self-locking of the mechanism, in both motion subsystems.

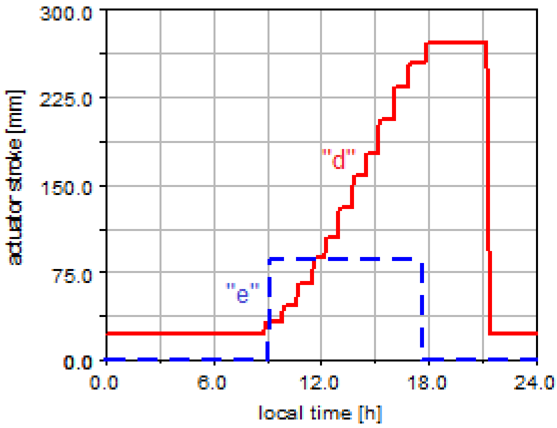

Fig. 10. The linear strokes of the actuators.

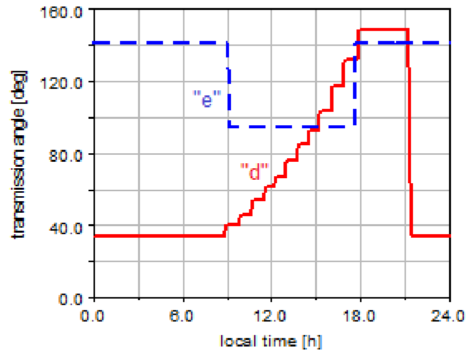

Fig. 11. The transmission angles in the tracking mechanism.

At it was mentioned, the optimization of the dual-axis tracking system was focused in two directions (i.e. design objectives), namely the minimization of the motor forces and of the tracking errors. The time-history variations of these functions are shown in Fig. 12 and 13. The variations of the motor forces, which obviously follow the profile of the laws of variation of the corresponding angles (see Figure 8) are relatively small, while the tracking errors are practically null (of the order of $10^{-5°}$), which leads to a very high orientation accuracy, relative to the imposed dual-axis tracking program.

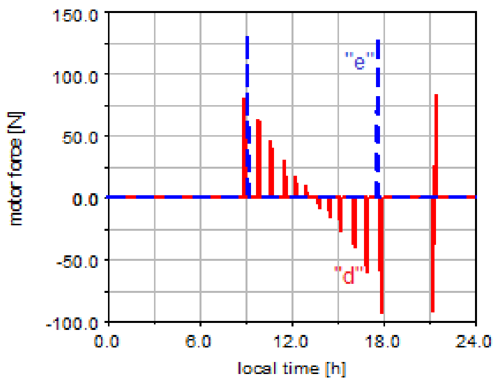

Fig. 12. The motor forces developed by the linear actuators.

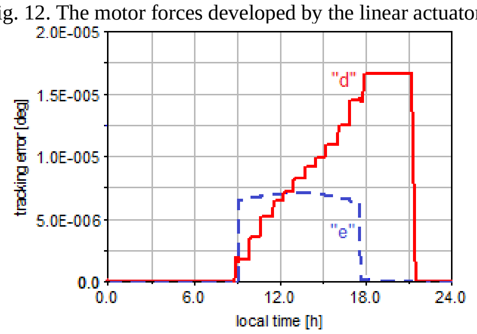

Fig. 13. The tracking errors.

The relatively low values of the motor forces are actually found in low consumption for achieving the tracking on the two axes of movement, as shown in Fig. 14, which has a beneficial effect on the energetic efficiency of the PV tracking system. The total energy consumption (which cumulates the energy consumed to achieve the two movements of the PV system) is 31.975 Wh/day.

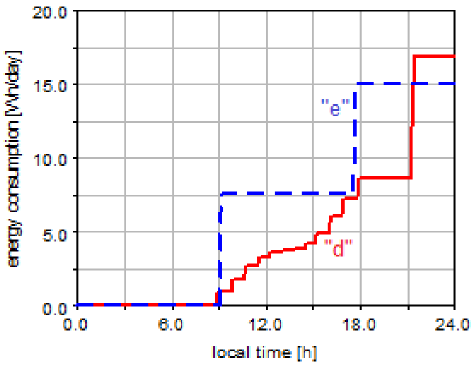

Fig. 14. The energy consumed to achieve the tracking.

The previously presented results prove the high efficiency of the proposed dual-axis tracking system and therefore the usefulness/viability of the multi-objective design algorithm through which it was optimized from the point of view of the mechanical and control subsystems (devices), in mechatronic concept. A more detailed study on the energetic efficiency of the PV tracking system, including by considering the amount of energy produced by the PV panel and its reporting to the case of the fixed equivalent reference PV system (without tracking), is to be presented in a future work.

Conflict of Interest

The author declares no conflict of interest.

Author Contributions

As the sole author, Cătălin Alexandru, conducted the whole research and wrote the paper.

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