

# MODELLING AND ANALYSIS OF THE PHOTOVOLTAIC TRACKING SYSTEMS AS MULTIBODY SYSTEMS

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**Abstract:** *In this paper we present the modelling and analysis process of the photovoltaic (PV) tracking mechanisms as multibody systems (MBS). The general steps for the MBS modelling are presented, along with the conditions in which the kinematic elements (parts) can be modelled as bodies (with mass & inertia properties) or composite restrictions. The modelling as multibody system is important, because on it depend on the complexity of the theoretical model, by decreasing the number of moving bodies, and consequently the number of unknown generalized coordinates. The application is made for the azimuthal tracking system of a PV platform. The dynamic model of the solar tracker is developed by using the MBS ADAMS software package.*

**Key words:** *multibody system, tracking mechanism, photovoltaic platform.*

## 1. Introduction

The solar energy conversion is one of the most addressed topics in the fields of renewable energy systems. The present-day techniques allow converting the solar radiation in two basic forms of energy: thermal and electric energy. The technical solution for converting the solar energy in electric energy is well-known: the photovoltaic (PV) modules.

The degree of use of the solar radiation can be maximized by use of tracking mechanisms for the orientation of the PV modules. Basically the tracking mechanisms are mechatronic systems, driven by rotary motors or linear actuators, which are controlled in order to ensure the optimal positioning of the PV module relatively to

the Sun position on the sky dome [1].

The realization of the photovoltaic arrays appeared as a necessity for the development of large systems for producing electric energy based-on the solar energy. A photovoltaic array is a linked collection of modules, which are in turn made of multiple interconnected solar cells. In practice, there are two solutions for developing the tracked arrays (groups of modules): array with individual modules, where the modules are separately mounted on individual supports; platforms, where the modules are mounted on a common frame (sustaining structure).

The PV platforms, even they involve inconvenient concerning the construction or integration in the built environment, have the advantage of a unitary electrical

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management and the structure is more compact than in the case of the array with individual modules.

Determining the real behaviour of the tracking systems is a priority in the design stage since the emergence of the computer graphic simulation. Important publications reveal a growing interest on analysis methods for multi-body systems that may facilitate the self-formulating algorithms, having as main goal the reducing of the processing time in order to make possible real-time simulation [3], [4].

In the last decade, a new type of studies was defined through the utilization of the MBS software: Virtual Prototyping [2], [5]. This technique consists mainly in conceiving a detailed model and using it in a virtual experiment, in a similar way with the real case. One of the most important advantages is the possibility to perform virtual measurements in any point or area, and for any parameter (motion, force).

Under these circumstances, the paper presents the modelling and analysis process of the photovoltaic tracking mechanisms as multibody systems. According with the MBS theory, a mechanical system is defined as a collection of bodies with large translational and rotational motions, linked by simple or composite constraints.

## 2. Modelling the Tracking Mechanism as Multibody System

For identifying accurate mechanical configurations suitable for the tracking systems, the structural synthesis was performed in the following stages: identifying all possible graphs, taking into account the space motion, the type of joints, the number of bodies, and the degree of mobility; selecting the graphs that are admitting supplementary conditions imposed by the specific utilization field; transforming the selected graphs into

mechanisms by mentioning the fixed body and the function of the other bodies, identifying the distinct graphs versions based on the preceding particularizations, transforming these graphs versions into mechanisms by mentioning the geometric constraints.

In this way, a collection of possible structural schemes of tracking mechanisms were obtained. The solution for tracking mechanism used in the study, which is a dual-axis azimuthal system (Figure 1), was selected from the multitude of the structural solutions by using of the multi-criteria analysis. The evaluation criteria of the solutions were referring to the tracking precision, the amplitude of the motion, the possibility for manufacturing and implementation.

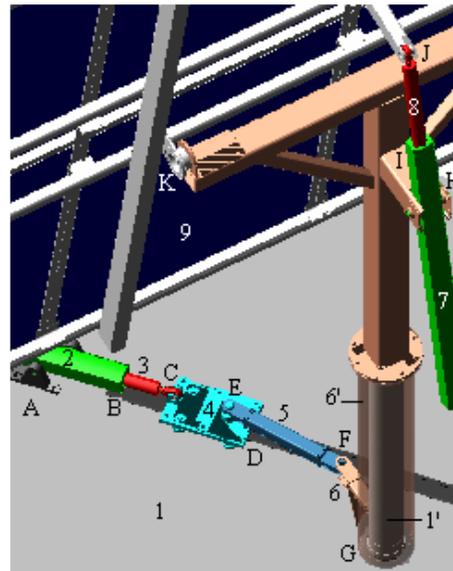


Fig. 1. *The azimuthal tracking system*

The driving source for the azimuthal motion is a linear actuator, the motion being transmitted to the sustaining pillar of the PV platform with a stroke amplifying system that contains a planar slider - crank mechanism. The inner tube of the pillar is

rigidly connected to ground, while the crank is fixed to the outer moving part of the pillar.

The altitudinal motion is also generated with a linear actuator, at which the cylinder is connected to the moving part of the pillar, and the piston acts directly on the platform. In this case there is no need for a stroke amplifying mechanism, because the angular field is less than in azimuthal motion (in the Braşov geographic area, the maximum angular field for the altitudinal motion is  $47^\circ$ , instead of  $180^\circ$  for the azimuthal motion).

In these terms, there can be identified the following components of the photovoltaic tracking system (Figure 2a - the azimuthal motion kinematic chain, b - the altitudinal motion chain):

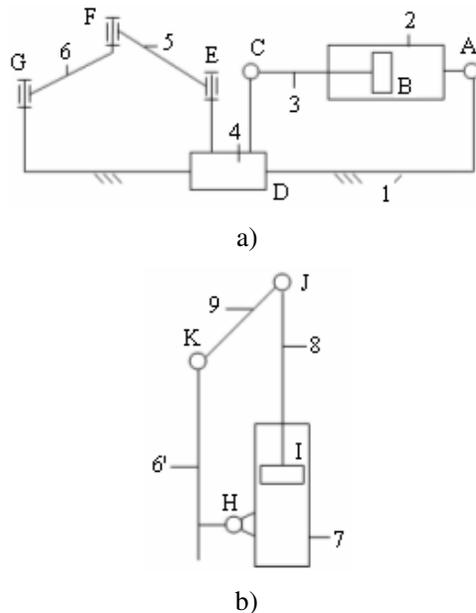


Fig. 2. *The structural model of the system*

- the fixed plate (1), rigidly connected to ground, including the inner part (1') of the sustaining pillar;
- eight moving parts (bodies): the cylinder (2) and the piston (3) of the linear

actuator which drives the azimuthal motion; the slider (4), the rod (5), and the crank (6) which is rigidly connected with the moving outer part (6') of the pillar; the cylinder (7) and the piston (8) of the linear actuator which drives the altitudinal motion; the photovoltaic platform (9), which includes eight photovoltaic modules and the sustaining frame;

- eight revolute joint (R), of which five belong to the kinematic chain of the azimuthal motion, and three to the altitudinal motion chain: A (adjacent parts: 2 - 1), C (3 - 4), E (4 - 5), F (5 - 6), G (6 - 1), H (7 - 6'), J (8 - 9), K (9 - 6');

- three translational joints (T), of which two belong to the kinematic chain of the azimuthal motion, and one to the altitudinal motion chain: B (2 - 3), D (4 - 1), I (7 - 8).

The modelling of the tracking mechanism as multibody system consists in the identification of the bodies, as well as the restrictions between them. From classical point of view, all kinematic elements (i.e. parts) of the mechanism can be modelled as bodies, and the geometric constraints are applied between these parts. There are some cases in which the kinematic elements can be modelled as composite joints between other parts (with massless intermediate element), for example constant distance or area restrictions. In this way, the multibody system model of the photovoltaic tracking mechanism will be simplified.

The kinematic elements of the mechanisms must be modelled as bodies (with mass & inertia properties) in the following situations: the element is input or output element; the element has three or more connections to other parts; the element is fixed (ground part); on the element, elastic and/or damping connectors are disposed; external forces/torques act on the element; the mass of the element is high, so that the mass & inertia properties have great influence on the mechanism's behaviour.

For the classic modelling case (all the kinematic elements modelled as bodies) there are  $n = 9$  bodies (8 moving bodies), which are connected through 11 geometric constraints (simple joints). By modelling the tracking system as multibody system (MBS), considering the above-presented conditions, there is obtained a model with the following structure (Figure 3):

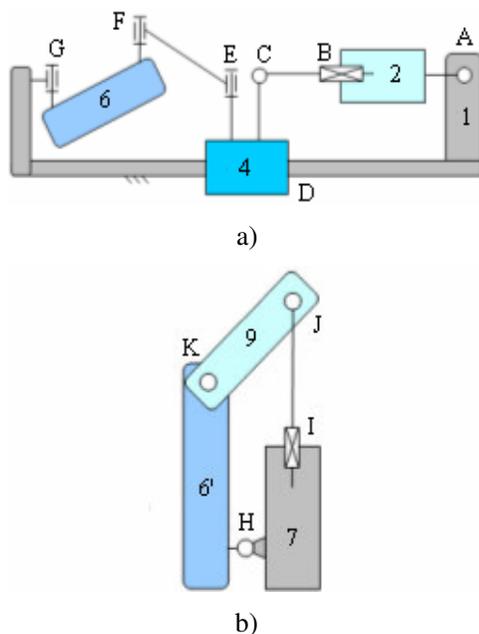


Fig. 3. *The MBS model of the mechanism*

- the fixed part (1);
- the slider (4) - body with three connections/joints (C, D, E);
- the output part (6) from the slider-crank mechanism, which is rigidly connected to the moving outer part (6') of the pillar - body with four joints (F, G, H, K);
- the cylinders of the linear actuators (2 & 7) - input bodies for the azimuthal and altitudinal motions;
- the photovoltaic platform (9) - output body for the both motions;
- three composite geometric constraints: BC - type TR / constant area (adjacent bodies:

2 - 4); EF - type RR / constant distance (4 - 6); IJ - type TR (7 - 9);

- five simple constraints: A, D, G, H, K (similar with the classic modelling case).

For the MBS modelling case, there are six bodies (five moving bodies), which are connected through eight geometric constraints, three of them being composite joints. Relative to the classic modelling case, by replacing bodies with composite constraints, there were eliminated three bodies (eighteen unknown generalized coordinates - six for each replaced body).

The major disadvantage of this modelling, in which the actuator cylinders are input bodies, with imposed motion, consists in the necessity to transpose the linear stroke of the actuator (the relative motion between piston and cylinder) in the rotation angle of the cylinder. Obviously, this correlation can be obtained from the kinematics of the mechanism, but the input data modelling is more complex.

Other modelling case as multibody system, which eliminates the previous disadvantage, consists in the modelling of the driving linear actuators as RR (revolute - revolute) composite constraints with variable distances (the distances AC and HJ vary according with imposed motion laws, which represent, in fact, kinematic restrictions). For this case, the MBS modelling leads to a system with the following structure (Figure 4):

- the fixed part (1);
- the slider (4) - body with three connections/joints (C, D, E);
- the output part (6) from the slider-crank mechanism, which is rigidly connected to the moving outer part (6') of the pillar - body with four connections/joints (F, G, H, K);
- the photovoltaic platform (9) - output body for the both motions (azimuthal and altitudinal);
- three composite geometric constraints: EF - type RR / constant distance (adjacent bodies: 4 - 6); AC & HJ - type RR / imposed variable distance (4 - 1 & 9 - 6');

- three simple geometric constraints: D, G, K (similar with the classic modelling case).

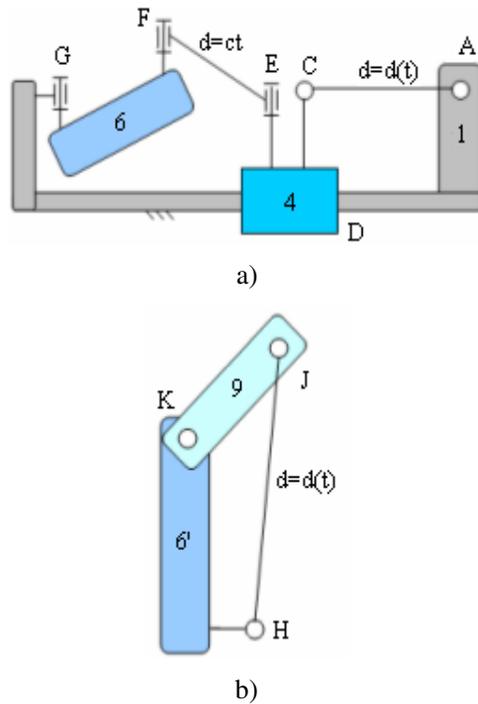


Fig. 4. *The MBS model with minimum number of bodies*

For this modelling case, there are four bodies, which are connected through six geometric constraints, three of them being composite joints. Relative to the classic modelling case, by replacing bodies with composite constraints, there were eliminated five bodies (thirty unknown generalized coordinates). Practically, this is the simplest MBS modelling case, with minimum number of bodies.

Concluding, the modelling as multibody system is very important, because on it depend on the complexity of the theoretical model. The modelling with minimum number of bodies minimizes the number of unknown generalized coordinates, and in consequence the number of equations.

### 3. Developing the Virtual Models

The tracking systems are, in fact, mechatronic systems, which integrates mechanics, electronics and informatics components. Integrating the control system in the mechanical model, we can verify from one database the combined effects of the control system on the multibody system model. The simulation process in the concurrent engineering concept creates a closed loop in which the control inputs from the control application affect the MBS simulation, and the MBS outputs affect the control input levels.

In our research, the MBS model of the tracking mechanism was realized by using the general pre-processing module from the ADAMS software package (namely, ADAMS/View), while the control system was developed by using the tools from the ADAMS/View Controls Toolkit. The detailed presentation of the control system, including the controller design & tuning, will be made in a future paper.

For developing the solid (geometric) model of the tracking system, we used the CAD software CATIA. The geometry transfer from CATIA to ADAMS was performed using the STEP file format, through the ADAMS/Exchange interface. The next stage consists in the modelling of the geometric constraints between bodies (simple and composite joints), according with the above-presented modelling cases. For the tracking system in study, there are the following models:

- the classic model with 9 bodies (Figure 5 - equivalent with Figure 2);
- the MBS model with 6 bodies (Figure 6 - equivalent with Figure 3);
- the MBS model with minimum number of bodies - 4 bodies (Figure 7 - equivalent with Figure 4).

For the MBS model shown in Figure 6, excepting the simple joints, there are three composite constraints, which replace the

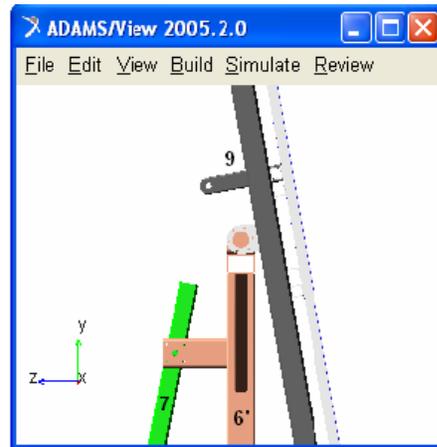
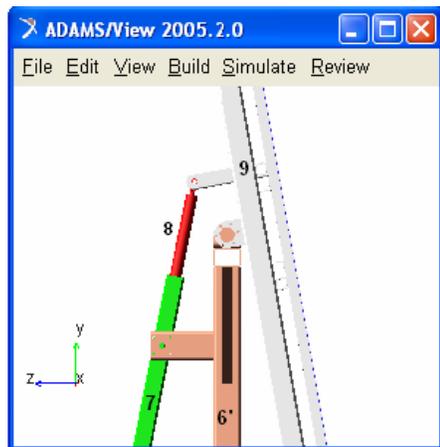
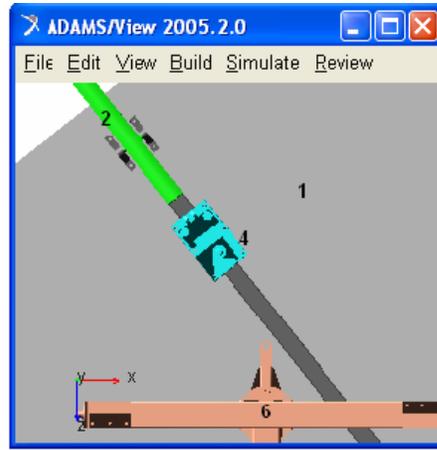
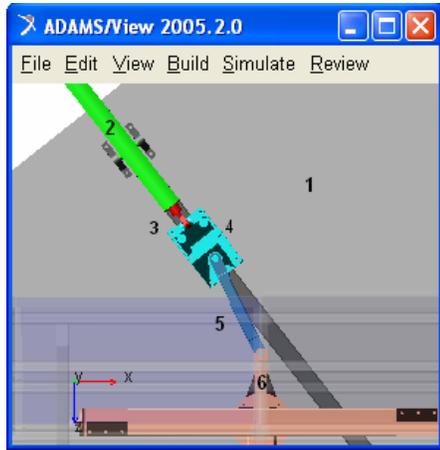


Fig. 5. *The virtual classic model*

Fig. 6. *The virtual MBS model*

actuators' pistons and the rod of the slider-crank mechanism. In ADAMS, the composite constraints have been modelled as general constraints of type  $f(q) = 0$ , by creating mathematic expressions in the Function Builder, as follows:

- the composite joint BC (constant area):  
 $DX(B) * DY(A) + DX(A) * DY(C) + DX(C) * DY(B) - DX(B) * DY(C) - DX(A) * DY(B) - DX(C) * DY(A) = 0$ ;
- the composite joint IJ (constant area):  
 $DZ(I) * DY(H) + DZ(H) * DY(J) + DZ(J) * DY(I) - DZ(I) * DY(J) - DZ(H) * DY(I) - DZ(J) * DY(H) = 0$ ;
- the composite joint EF (constant

distance):  $DM(E, F) - 0.45 = 0$ , in which 0.45 is the length of the rod (in meters).

The expressions contain the run-time functions: DX/Y/Z (Distance along X/Y/Z) - returns an X/Y/Z component of the translational displacement vector from one marker (A, B, C, I, J, H) to the global coordinate system; DM (Distance Magnitude) - returns the magnitude of the translational displacement vector from one marker (E) to another (F).

For the MBS model with minimum number of bodies (Figure 7), in addition to the composite constraints EF, there are two composite joints of variable distance,

which are imposed by the motion laws of the driving actuators, as follows:

- the composite joint AC:  $DM(A, C) - AKISPL(time, 0, SPLINE\_1, 0) = 0$ ;
- the composite joint HJ:  $DM(H, J) - AKISPL(time, 0, SPLINE\_2, 0) = 0$ .

These expressions impose to annul the difference between the current distance from one coordinate system marker (A, respectively H) to another (C, respectively J) and the similar distance from the classic model (see Figure 5), which have been stored/saved as Akima Spline functions.

#### 4. Results & Conclusions

The tracking laws were developed considering the correlation between the maximum amplitudes of the motions, the number of steps, and the actuating time [6]. The simulations are made considering the summer solstice day, with the following input data: the angular field for azimuthal motion -  $\psi^* \in [90^\circ, -90^\circ]$ , the angle being null at the solar noon; the field for altitudinal motion -  $\alpha^* \in [10^\circ, 67^\circ]$ , the angle being null when the platform is vertically disposed. In these terms, the motion laws are shown in Figure 8.

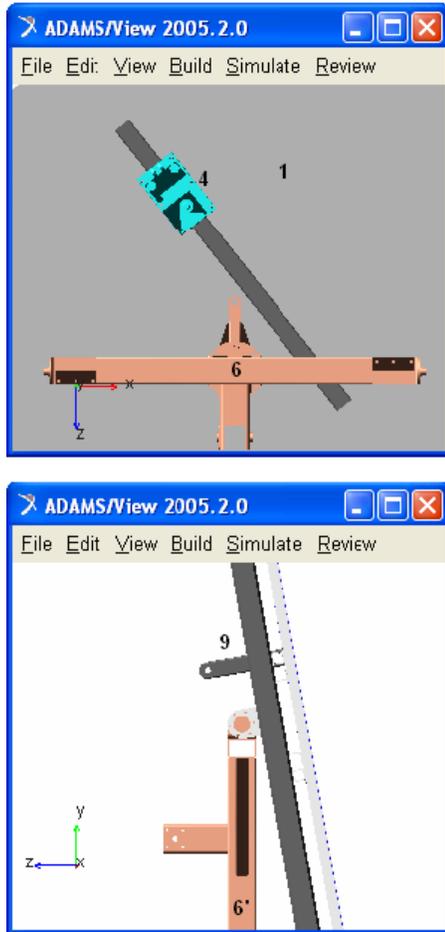


Fig. 7. *The virtual MBS model with minimum number of bodies*

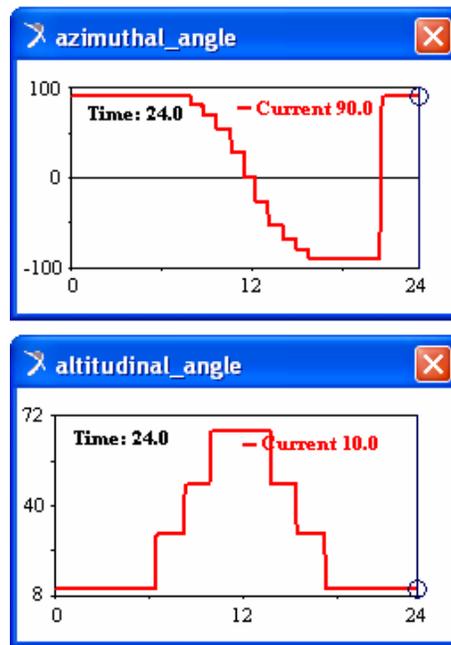
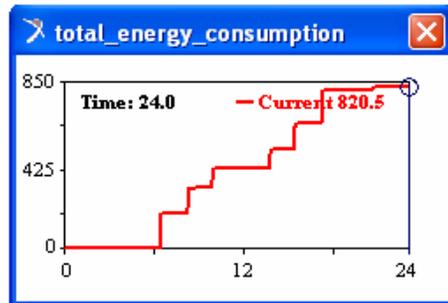
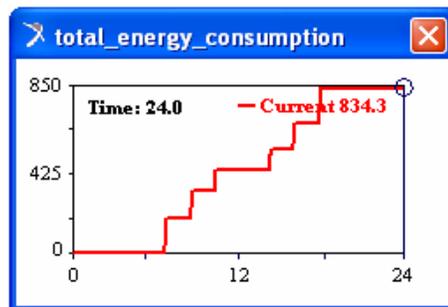


Fig. 8. *The motion laws of the PV platform*

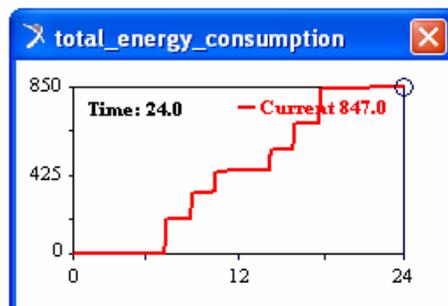
The interest parameter is the energy consumption for realizing the orientation (in [Wh/day]). The results obtained for the three models in study are shown in Figure 9: *a*) the classic model (see Figure 5), *b*) the MBS model (Figure 6), *c*) the MBS model with minimum number of bodies (Figure 7).



a)



b)



c)

Fig. 9. The results of the analyses

The results correspond to the dynamic model, which takes into account the mass forces, the reaction in joints, and the joint frictions. The main part of energy is consumed to overcome the mass forces. For the azimuthal motion, the consumption is small, because the mass forces are downloaded in the vertical pillar. Thus, most of the energy consumption is due to

the altitudinal motion.

Strangely, the energy consumption for the altitudinal tracking is lowest for the classic model (Figure 5), where is the largest mass loading, all kinematic elements being modelled as bodies. This is because the linear actuator acts as a counterweight, while in the MBS models (Figures 6, 7) it is partially or wholly neglected in terms of mass, being modelled as composite joints.

Concluding, the differences between the results (which, however, are small) are mainly caused by how the altitudinal actuator is modelled. For minimizing the energy consumption, a supplementary balance from altitudinal mechanism point of view is necessary. This will be a topic for future researches, along with the evaluation of the energetic gain for different tracking modes/strategies.

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