Artificial Intelligence to Aid the Efficient Dynamic Behavior of the Dual-axis Solar Tracking System

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***Abstract*— Renewable energy applications rely heavily on the use of Artificial Intelligence and machine learning. The new global energy economy is gaining momentum as photovoltaic solar energy accelerates worldwide. Several solar panels have been installed in the direction of maximum solar radiation for various applications around the world. But in the case of moving platforms, for instance, an application like ships, military vehicles, satellites, etc., the maximum solar radiation at all the positions and displacements is not obtained. In addition, the sun is still in motion depending on the variation of the calendar. Consequently, there are problems with the energy collected by solar panels and their production which differs considerably at different times, positions, and bearings. This research work aims to model the dynamic behavior of a 2-DOF mechanism that can be used as a dual-axis solar moving base. As a verification, the equation of motion examines several important issues in implementing an expert system for the robust controller design of the proposed intelligent mechanism. Accordingly, the proposed algorithm of moving bases and tracking systems is the most efficient way to get maximum radiation and therefore implement maximum productivity with minimum losses for faster displacement of moving platforms with solar panels. It is evident that the movement of the panels toward the direction of solar motion uses the maximum radiation at all times, and as a result, the higher efficiency of the solar panels is achieved.**

Keywords*— *Expert Systems; Artificial Intelligence; Tracking the Sun; Base Solar Panel; Dynamic Equation; Stepper Motor.

I. INTRODUCTION

The maximum radiant energy collected on solar panels only appears at one time a day [1-3]. Tracking the sun is the best way to receive maximum radiation [4, 5].

The research work presents a methodology for modeling incremental electrical motors actuated positional manipulator structure, for point-to-point (PTP) movement control. A simplified strategy for fast-time and efficient control has been developed. This is called "Expert Trapezoidal Control", the method enables a considerable simplification of the complexity of hardware and software and proves to be eminently suitable for applications where continuous movements of solar panels are provided [6]. The new approach of designing a prototype system for the solar tracker is developed so that it is expected the proposed mechanism can reduce the power load generated by solar panels to the drive units of the moving joints and therefore improve the total efficiency of the system [7].

For point-by-point control applications, where the basic mechanisms are required to follow specified trajectories, a strategy based on a modified form of expert system control is proposed. This methodology has been extensively tested by simulations and experimental research on a laboratory prototype, with very acceptable results. The proposed sun monitoring mechanism is illustrated in Figure 1. The solar panel is mounted to the top of the base of the rotating table through the support of the movable hinges. The azimuth stepper motor can transmit the power to the support beam through the rotary table and gear_2 can drive gear_1 through a gearbox which can orientate the solar panel in 3-D movement [8].

In general, the dynamic performance and efficiency of a moving system directly depend on the efficiency of its dynamic model and the control algorithms [9-11].

In so far as the proposed solar panel moving base is concerned, deciding the methodology for control of the system may be achieved based on:

- formulating the dynamic model of the physical system
- incorporating the actuator characteristics under typical types of load conditions envisaged in the operation
- specifying suitable intelligence control strategies to achieve the best possible system response and performance

II. STUDY OF THE PROBLEM

In general Photo voltaic panels work more efficiently when their absorbing surface is perpendicular to the sun's position taking into account the panel's zenith orientation and tilt angle.

Even though the moving positioning base and the solar tracker itself have certain disadvantages with the power consumption drive, the motors have a fairly large power to displace the solar panel and continuously follow the movement of the sun concerning the position displacement of the base or the portable platform which solar panels are installed and fixed on the two degrees of freedom manipulator's base mechanism [8]. Rotary-rotary (RR) positional moving base mechanisms find extensive use in

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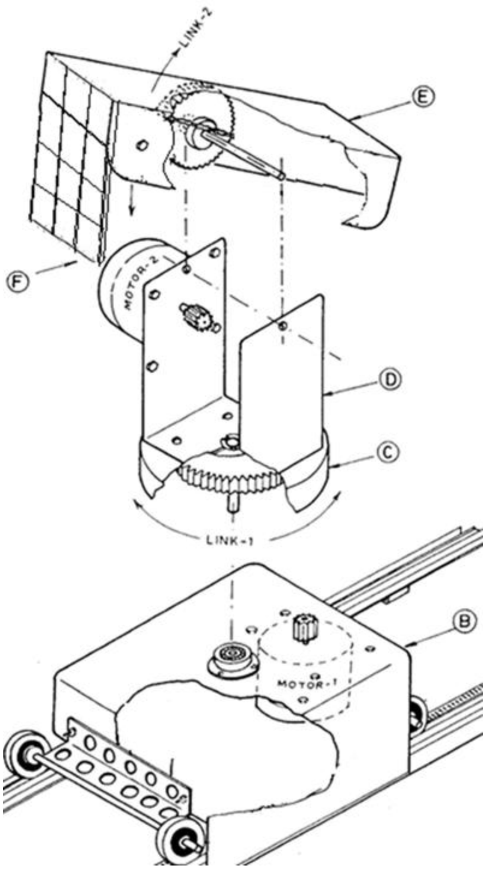
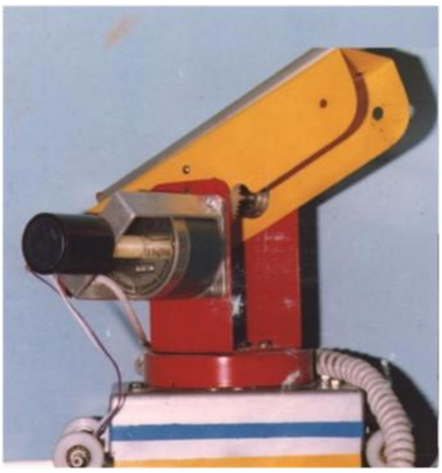
diverse industrial and supervisory applications. The use of the stepper motors as the joint driving units in such moving platforms has special attractions because of their inherent compatibility with digital control mechanisms, simplicity, and convenience in operation even in open-loop control mode with little cumulative positional error, high accuracy in response to the input signal, and position control ability with minimum possibilities of overshooting under transient conditions, together with high stability in operation even under changing conditions of-actuator parameters over wide speed ranges.



(a)



(b)

Fig. 1. The complete arrangement of the proposed experimental moving base assembly, designed and fabricated by the author

The scope of the present "Expert System" focuses on integrating moving solar panel base systems with faster time and higher efficiencies for commonly encountered displacement problems and focusing on the sun's rays according to Geographic location, Time of day, Season, Local landscape, Local weather, etc.,

An experimental prototype moving base was developed to verify the simulation results and illustrate the efficiency of the proposed approach. After adjusting the design parameters of the moving base, the stepper motor drive units are operated in optimum position control mode.

Deciding what action to take

Expert System Fundamental and Development

Using continuous movement along with consuming required energy by driving units of the base moving structure of panels in the direction of the sun, the maximum radiation can be utilized.

The initial focuses of artificial intelligence and expert systems were on theorem proving and general problem-solving. Digital computers were initially intended to be high-speed data processors for performing numerical computations, predominately in the early days of their creation, there was a small group of dedicated computer scientists devoted to algorithms and software which attempted to emulate some of the activities of human decision-making processes [17]. The present work focuses on the architecture of the dynamic expert system, robust controller design methods, implementation of knowledge bases, and the integration of these to form a useful efficient controller design proposal.

The main fundamental requirements of an expert system process are based on 'expert', 'Knowledge engineer', and 'User' as defined below:

- Expert: person with extensive knowledge or ability.
- Knowledge engineer: professional engaged in the science of building advanced logic into computer.
- User: system developed by an end user with a simple shell, is built rather quickly and inexpensively.
- Problem identification and feasibility analysis:
- System Design and Expert System Technology Identification:
- Development of prototype system:
- Finding out how well the prototype works and its refinement:
- Rules of the expert system:
- Maintain the system:

Development of Expert System

Artificial Intelligence (AI) is a research field between psychology, cognitive science, and computer science with the overall goal of improving the reasoning capabilities of computers [15, 18-20].

Reduction and devaluation of the human expert's involvement in the control process have taken place due to the recent developments in modern AI tools.

Knowledge built into an expert system may originate from different sources. The prime source of knowledge for developing an expert system should be the domain expert. To design and develop the knowledge-based expert system, the specific knowledge domain or the subject domain must be acquired. The knowledge domain is to be organized so that the information can be structured in a computer program for effective use. In this respect, a knowledge engineer usually obtains knowledge through direct interaction with the expert. Fig.2 illustrates the process of data procurement for generating the knowledge base. Artificial Intelligence is widely used in solar panel applications. Radiations being of different types provide different power outputs from the panel at different tilt and azimuth angles. Thus, the tilt and azimuth angle, if optimized, can yield more power from the same solar panel. The possibility of developing a machine that would optimize the position has intrigued the users to reduce the human expert involvement in the positioning control process and has gradually taken place upon the recent developments in modern intelligence control tools. Artificial neural networks (ANNs) and expert systems based on fuzzy logic are good candidates for the automation of position control procedures and pointing applications. The present work surveys the principles and criteria of the efficient positioning process and introduces the current research achievements to apply expert system techniques in the optimization and orientation of solar panel positioning. In this presentation, a new technique is discussed and experimental results are presented for an expert system application. The chapter outlines an understanding of how expert systems and intelligent networks operate by way of presenting several problems in the different disciplines of solar panel positioning engineering [21, 22].

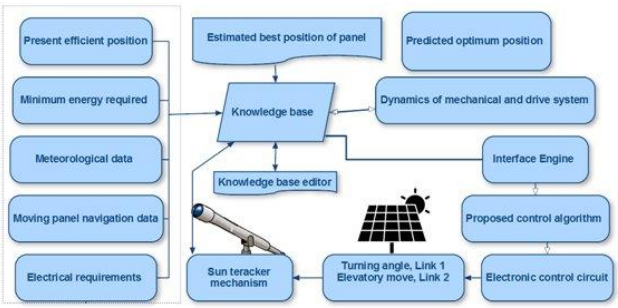


Fig. 2. The process of data procurement for generating the knowledge base.

The tracker provides additional safety to the panel from shadows reducing the possibility of the hot-spot effect significantly [23]. Solar radiation position information is usually measured in the form of global and diffuse radiation on a horizontal surface. Flat-plate solar photo voltaic collectors are tilted to capture the maximum radiation. The problem of calculating solar radiation on a tilted surface is in determining the relative amount of beam and diffuse radiation contained in the measured horizontal global radiation using exact calculation and formulation of the position of the solar panel's orientation. An intelligent automatic solar tracker is a device that orients and optimizes a payload toward the sun. Such a programmable expert system solar tracking device includes principles of solar tracking systems, as well as a mechatronic solar tracking controller to orientate solar photovoltaic panels, solar lenses, the structure of panels, or other optical configurations towards the sun's direct radiation.

The proposed solar panel positional moving base mechanism, in its simplified form, can be looked upon as a three-dimensional robotic system of the rotary-rotary (RR) type. Formulation of the kinematics of the system incorporating the drive units and moving platform dynamics led to the realization of the basic equations of motion for the moving base mechanism [24].

The structural schematic of the positional system, considered for the present analysis, is depicted in Fig.3. For simplicity, the proposed schematic is attributed with two degrees of freedom, permitting the base (Link 1) to turn about the vertical axis (denoted by α) and Link 2 to rotate about the horizontal axis (denoted by β). For purposes of positioning, therefore, the control coordinates of consequence are α, for Link 1 and β for Link 2.

III. THE MATHEMATICAL MODELING

The actual dynamic modeling of the solar panel manipulators can be obtained from physical laws such as the laws of Newtonian mechanics and Lagrangian mechanics. This is the base for the development of a dynamic Equation of motion for the various manipulator arms in terms of specified geometric and inertial parameters of the links. Different methods, like the Lagrange Euler (L.E.) and Newton-Euler (N.E.), could be applied for obtaining equations of motion for the actual moving base mechanism. Alternatively, equations can be derived using computer programs designed for these equations can be this purposes (27-29). The implementation of a dynamic control system for the proposed prototype model has been introduced using different strategies based on turning in the minimum possible time and highest energy-efficient drive system output, discussed in the following sections. The steps followed in these sections are an integrated part of the design strategy for this configuration of the solar panel/pointing system.

Problems associated with turning a system of rigid bodies must be taken into account while designing the control strategy of the moving base and the solar panel manipulator system [28, 30].

A rigid body can be turned around a given axis more quickly if its moment of inertia is small concerning that axis. Fig.1 depicts the structural schematic of the proposed solar panel moving base with two degrees of freedom, admitting the base to turn around the vertical axis and a link rotation to be possible around the horizontal axis. The two controlled coordinates incorporated in the system may be defined as:

Turning angle, Link 1

Elevator moving base, Link 2

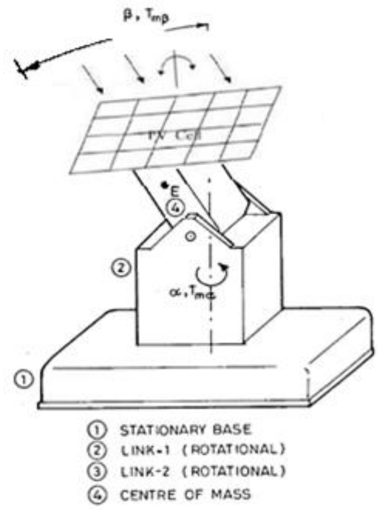


Fig. 3. Sketch of moving base proposed solar moving base.

A. *The dynamics of the solar panel moving base*

By variation of the position of Link 2, it is possible to change a system mass moment of inertia about the axis of turning. The strategy of control of a system of rigid bodies including the consumed energy could be based on consideration of minimum turning time, and this would involve a study of how the moment of inertia of the system behaves under such control strategies.

Concerning the schematic arrangement of Fig.3 let "α" denote the angle of the base turning in the horizontal plane and "β" the angle of the link turning along the vertical plane. The actuating signals Tα and Tβ are generated employing two drive units using stepping motors installed suitably through gear assembly arrangement, with gear ratios σα and σβ.

The base moment of inertia relative to the vertical axis is denoted by J. the Link mass by m, and the distance from the Link axis of rotation to its center of mass, (point E), by l. A, B, and C link moments of inertia in the main central axes of rotation with the axis of consideration passing through point E.

B. *Dynamic modeling of moving base mechanism:*

It is readily seen that including the change of dynamic characteristics of moving elements of the base mechanism, and variation in the position of Link 2, leads to a change in the system moment of inertia concerning the main turning axes of the positioning device.

The effect of changing the moment of inertia due to positioning and displacement of moving elements of the base are formulated according to the following considerations:

Let the moment of inertia of the base (Link 1) concerning the vertical axis be denoted by 'J', the mass of Link 2 by 'm', and the distance between the center of mass of Link 2 (point E in Fig.2) and the axis of its rotation be denoted by 'l'. Furthermore, let 'A', 'B', and 'C' represent the moments of inertia of Link 2 relative to the principal axis of rotation of the moving base with the axis of consideration passing through point E. The joints are considered as driven by individual stepper motors with actuating torques of the Tα and Tβ, through gear assemblies with gear ratios 'σα' and 'σβ.

The basic equation of motion is corrected using the new version of the dynamic modeling of 2 degrees of freedom R-R moving base (31).

$$T_\alpha = \{J_\alpha + B + (m_\beta l_\beta^2 + C - B)\sin^2\beta\}\frac{d^2\alpha}{dt^2} + \{(m_\beta l_\beta^2 + C - B)\sin^2\beta\}\dot{\alpha}\dot{\beta}$$

$$T_\beta \left\{\frac{m_\beta l_\beta^2 + A}{J_\beta}\right\}\frac{d^2\beta}{dt^2} - \frac{1}{2}(m_\beta l_\beta^2 + C - B)\sin^2\beta\left(\dot{\alpha}\right)^2 - m_\beta g l_\beta \sin\beta \quad (1)$$

Were

$$\mathbf{J}_{\boldsymbol{\beta}} = \boldsymbol{A} + \mathbf{m}\boldsymbol{l}^2 \boldsymbol{sin}^2\boldsymbol{\beta} = \boldsymbol{m}(\boldsymbol{r}^2 + \boldsymbol{l}^2\,\boldsymbol{sin}^2\boldsymbol{\beta})$$

And 'r' is the horizontal displacement of the form horizontal displacement of the center of mass of Link 2 from the principal vertical axis of rotation of the moving base.

On the assumption that the mass of Link 2 is so small that the effects of B and C in relations (1) above can be ignored, the above expression may be simplified to yield joint torques:

$$\boldsymbol{T_\alpha} = \left(\boldsymbol{J_\alpha} + \boldsymbol{m_\beta l_\beta^2}\,\boldsymbol{sin^2\,\beta}\right)\frac{\boldsymbol{d^2\alpha}}{\boldsymbol{dt^2}} + \left(\boldsymbol{m_\beta l_\beta^2}\,\boldsymbol{sin\,2\,\beta}\right)\dot{\boldsymbol{\alpha}}\dot{\boldsymbol{\beta}}$$

$$\boldsymbol{T_\beta} = \boldsymbol{J_\beta}\cdot\frac{\boldsymbol{d^2\beta}}{\boldsymbol{dt^2}} - \{\frac{\boldsymbol{m_\beta l^2\beta}}{\boldsymbol{2}}\boldsymbol{sin^2\,\beta}\ \}\dot{\boldsymbol{\alpha}}^{\boldsymbol{2}} - \boldsymbol{m_\beta g l_\beta\, sin\,\beta} \quad (2)$$

'g' is the acceleration due to gravity.

C. *Equations governing stepper motor dynamic load of the system:*

Hybrid, two-phase stepper motors, working on the two-phase-on mode of switching, find great favor as the driving units for the positional base manipulators of solar panels. Because of open loop control abilities, they are capable of developing acceptable efficiency, and the high torque-to-weight ratios. The dynamic torque equation for this type of machine has been developed and shown as follows [32, 33].

$$\boldsymbol{T_m} = \boldsymbol{PG}\{\boldsymbol{i_{1s}}\,\boldsymbol{sin}(\boldsymbol{Nr\,\theta}) + \boldsymbol{i_{2s}}\,\boldsymbol{cos}(\,\boldsymbol{Nr\,\theta})\} \quad (3)$$

Where,' G' is the machine constant, 'Nr' is the number of rotor teeth, 'i1s' and 'i2s 'the instantaneous currents in windings 1s and 2s respectively, 'p' is the number of stator pole-pairs, and 'θ' is the rotational angle in radians. It is a common practice to ignore the effects of the harmonics of the pulse-shaped currents and assumes:

$$\boldsymbol{i_{1s}} = \boldsymbol{I_m}\,\boldsymbol{cos}\,\boldsymbol{\omega}\,\boldsymbol{t}\boldsymbol{i_{2s}} = \boldsymbol{I_m}\,\boldsymbol{cos}(\,\boldsymbol{\omega t} - \frac{\boldsymbol{\pi}}{\boldsymbol{2}}) \quad (4)$$

Where 'ω' is the angular frequency of the pulse signal.

Equations of motion of the R-R positional base system

Equations of motion, governing the working of the joint drive units, can be readily obtained, and shall have the form:

$$\left(\frac{J_{m\alpha}}{\sigma_\alpha}\right)\frac{d^2\alpha}{dt^2}+\left(\frac{D_{m\alpha}}{\sigma_\alpha}\right)\frac{d\alpha}{dt}\sigma_\alpha T_\alpha = T_{m\alpha}$$

$$\left(\frac{J_{m\beta}}{\sigma_\beta}\right)\frac{d^2\beta}{dt^2}+\left(\frac{D_{m\beta}}{\sigma_\beta}\right)\frac{d\beta}{dt}\sigma_\beta T_\beta = T_{m\beta} \quad (5)$$

where Jm denotes the moment of inertia of the motor, Dm, the viscous friction at the motor end, T, the load torque, and Tm, the motor torque; α and β are the angular coordinates as already elaborated earlier. Expressions 2 and 3 are suitably combined to yield the dynamic equations of the manipulator system, as shown below:

$$\left[\frac{J_{m\alpha}}{\sigma_\alpha}+\sigma_\alpha\{J_\alpha+ml^2sin^2\beta\}\right]\ddot{\alpha}$$

$$+\sigma_\alpha ml^2sin^2\beta\,\dot{\alpha}\dot{\beta}+\frac{D_{m\alpha}}{\sigma_\alpha}\dot{\alpha}= T_{m\alpha}$$

$$\left[\frac{J_{m\beta}}{\sigma_\beta}+\sigma_\beta J_\beta\right]\ddot{\beta}-\frac{\sigma_\beta}{2}ml^2sin^2\beta\dot{\alpha}^2$$

$$+\frac{D_{m\beta}}{\sigma_\beta}\dot{\beta}-\sigma_\beta mglsin\beta = T_{m\beta} \quad (6)$$

Which can be denoted in the form:

$$J*_\alpha\ddot{\alpha}+D*_\alpha\dot{\alpha}+d_\alpha=T_{m\alpha} \quad (7)$$

$$J*_\beta\ddot{\beta}+D_\beta\dot{\beta}+d_\beta=T_{m\beta} \quad (8)$$

$$J*_\alpha=\frac{J_{m\alpha}}{\sigma_\alpha}+\sigma_\alpha\{J_\alpha+ml^2\,sin^2\beta\}$$

$$J*_\beta=\frac{J_{m\alpha}}{\sigma_\alpha}+\sigma_\beta J_\beta$$

$$D*_\alpha=\frac{D_{m\alpha}}{\sigma_\alpha}\ ;\ D*_\beta\frac{D_{m\beta}}{\sigma_\beta}$$

$$d_\alpha=\sigma_\alpha ml^2sin^2\beta\dot{\alpha}\dot{\beta} \quad (9)$$

$$d_\beta=-\frac{\sigma_\beta}{2}ml^2sin^2\beta\dot{\alpha}\dot{\beta} \quad (10)$$

$$d_\beta=-\frac{\sigma_\beta}{2}ml^2sin^2\beta\dot{\alpha}^2-\sigma_\beta mgl\sin\beta$$

and

$$T_{m\alpha}=P_\alpha G_\alpha[i_{1s\alpha}\sin(N_{r\alpha})+i_{2s\alpha}\cos(N_{r\alpha})] \quad (11)$$

$$T_{m\beta}=P_\beta G_\beta[i_{1s\alpha}\sin(N_{r\beta})+i_{2s\beta}\cos(N_{r\beta})] \quad (12)$$

For which

$$i_{1s\alpha}=I_{m\alpha}\cos\omega_{\alpha^t} \quad (13)$$

$$i_{2s\alpha}=I_{m\alpha}\cos\left(\omega_\alpha t-\frac{\pi}{2}\right)$$

$$i_{1s\beta}=I_{m\beta}\cos\omega_\beta\,t$$

$$i_{2s\beta}=I_{m\beta}\left(\omega_\beta t-\frac{\pi}{2}\right) \quad (14)$$

Evolution and expansion of expert trapezoidal control law strategy

IV. EVOLUTION AND EXPANSION OF EXPERT TRAPEZOIDAL CONTROL LAW STRATEGY

Control consideration demands analysis for two types of operations moving bases, namely, the point-to-point (PTP) and point-by-point (PBP) models [34]. The former is valid for unconstrained manipulation over a large distance desired when the system is required to follow a specified or pre-defined trajectory.

In a large number of applications, an additional device is required to operate at its highest possible efficiency and speed to minimize the task cycle time. In general, different ingestion of the time-optimal problem of moving base manipulator of the maximum power point tracking (MPPT) to transform its end-effector from an initial position to a specified destination in the minimum time during the continuous change of orientation [35]. The control strategy proposed by many researchers is too complex for easy implementation in real-time situations [36, 37]. The proposed modified control strategy with a velocity profile is better suited for real-time situations. While aiming at reducing the time of movement, the determination of the desired speed profile is also influenced by:

- Efficiency improvement during the positioning of the solar panels
- Accuracy with which the moving base platform of solar panels is positioned
- Effective payload mass of moving platform, including solar panels, to be manipulated
- increased distance of the desired movement

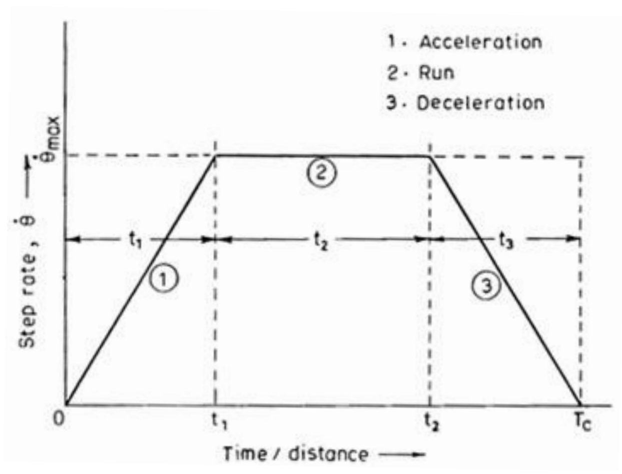


Fig. 4. Dynamic characteristic of load in expert trapezoidal control law strategy

V. Concluding Remarks

The research work recorded in the present chapter highlights the design, implementation, and test of the artificial intelligence solar panel tracking system with the use of a simple mathematical and simulation model of a two-phase hybrid stepper motor drive, formed by a particular process in a fabricated model.

In the mechanical design phase of the moving base, there are no efficient means except simulation to investigate and evaluate the performance of the proposed system.

It is of special importance that the designer grasps the characteristics of a detailed solar tracking platform well. Modeling of a moving base provides a method for determining these characteristics and this is possible through the formulation of mathematical equations. These equations deal directly with the dynamic equations of the system. Dynamic equations deal with the necessary forces or torques to be applied to different joints of the moving platform as a function of the required efficiency, position, velocity, and acceleration of the joint. Once the dynamic equations are well defined and constraints are entered, the torque or force to be applied to a joint can be accurately predicted by the expert system. Additionally, dynamic performance is one of the most significant factors in designing mechanical platforms, particularly, for efficient, fast, and accurate applications.

Realization of the desired characteristics, however, still needs efficient analysis of the behavior of the proposed system. The mechanical design parameters can be determined exactly and precisely if the dynamics of the drive units are added to the mechanical design parameters. Therefore, it is surmised that although consideration of mechanical parameters introduces additional complexities in equations denoted by "2", it may be effectively used as criteria for the systematic study and observation of design parameters and their effects on the general performance of the moving base under the constraints imposed by the required parameters of the design.

The proposed expert system and control details of the solar moving platform for a satisfactory solution related to its use for a fast time and efficient application based on point to point control are presented. The most attractive feature of PTP based strategy is its ability to use a simple administration algorithm with prerequisites for precise knowledge of the system time constants calculated and evaluated in the proposed expert system. This singular feature makes the strategy ideally suited for online positioning with fast time and efficient applications. At the same time, if the involved distance to be displaced is short, the control law required has to be modified suitably. For such an application, a closed-loop control scheme based on maximum allowable speed will be necessary. The controller dictates the moving platform to follow the response of the selected model for the entire operating range. So, further comparative study into stepper motor power consumption shows that the PTP tracking system can save more power compared to the continuous tracking system. Other than this, the designed tracking system can also be implemented for solar thermal systems. Finally, the proposed design is achieved with higher energy efficiency, high time response, and lower human involvement and is more cost-effective.

For high operating speeds, mechanisms should be lightweight to make a possible reduction in the driving torque requirements and to enable the moving base to respond faster and more efficiently. Lightweight platform structures are also desirable for specific applications like in space etc. However, light members are likely to deform elastically, thus making it necessary to take into consideration the dynamic effects of distributed link flexibility. Photovoltaic tracker systems represent an important area in which a significant amount of research has been carried out. However, the field itself is so vast that there is always room for innovation or improvement.

This created an overall increase in power output by the solar panel compared to a stationary model. The simulation results proved that the proposed expert system is more efficient than the regular conventional methods. Finally, future developments may also concern the application and improvement of the dynamic behavior of moving base using different methodologies and algorithms.

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